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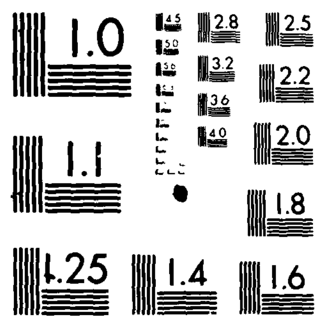


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Systems Research &
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Washington, D.C. 20590

# Operational and Functional Requirements for the Navigational System in Terminal Areas

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McLean, Virginia 22102

February 1982

Final Report

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U.S. Department of Transportation
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## NOTICE

**Technical Report Documentation Page**

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16. Abstract


A comprehensive set of operational requirements relating the capabilities of the navigation system and its use in the ATC environment are developed in this paper by modifying the operational requirements for MLS established by the International Civil Aviation Organization. In order to establish the functional requirements, an interrelationship is established between the navigation system parameters, route geometry and ATC procedures considering system uncertainties. An impact of each ATC uncertainty (navigation, surveillance, communication delays, airspeeds and winds) is first examined individually by computing the time dispersions between the planned vs. the achieved aircraft performance. Then a total dispersion and control interaction is established by calculating the time variability due to speed adjustments permitted under ATC procedures, and by statistically combining the impact of the ATC uncertainties using a root sum square (RSS) approach. This technique is general enough to permit evaluation of functional requirements (accuracy, coverage and channel capacity) of any navigation system under varying ATC parameters, procedures and operational requirements. Several navigation scenarios are evaluated based on the existing and future capabilities of the navigation systems. These include 1) existing VOR/DME systems with airline quality avionics, 2) existing, VOR/DME system with a $\pm 40^{o}$ MLS providing guidance within the coverage, and 3) a highly accurate navaid such as DAS (DME/Azimuth system) proposed by the Federal Republic of Germany. The main assessment criteria used are interarrival dispersions on final approach, relating capacity and controller workload. Based on the analytical results the functional requirements of a DAS type airport-based rho/theta system are established if such a system were to operate under a potential future ATC environment similar to Chicago or San Francisco using some level of automation.


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# METRIC CONVERSION FACTORS

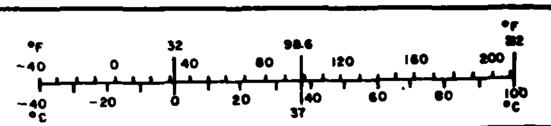
## Approximate Conversions to Metric Measures

| Symbol | When You Know | Multiply by | To Find | Symbol |
|---|---|---|---|---|
| | | **LENGTH** | | |
| in | inches | *2.5 | centimeters | cm |
| ft | feet | 30 | centimeters | cm |
| yd | yards | 0.9 | meters | m |
| mi | miles | 1.6 | kilometers | km |
| | | **AREA** | | |
| $in^2$ | square inches | 6.5 | square centimeters | $cm^2$ |
| $ft^2$ | square feet | 0.09 | square meters | $m^2$ |
| $yd^2$ | square yards | 0.8 | square meters | $m^2$ |
| $mi^2$ | square miles | 2.6 | square kilometers | $km^2$ |
| | acres | 0.4 | hectares | ha |
| | | **MASS (weight)** | | |
| oz | ounces | 28 | grams | g |
| lb | pounds | 0.45 | kilograms | kg |
| | short tons (2000 lb) | 0.9 | tonnes | t |
| | | **VOLUME** | | |
| tsp | teaspoons | 5 | milliliters | ml |
| Tbsp | tablespoons | 15 | milliliters | ml |
| fl oz | fluid ounces | 30 | milliliters | ml |
| c | cups | 0.24 | liters | l |
| pt | pints | 0.47 | liters | l |
| qt | quarts | 0.95 | liters | l |
| gal | gallons | 3.8 | liters | l |
| $ft^3$ | cubic feet | 0.03 | cubic meters | $m^3$ |
| $yd^3$ | cubic yards | 0.76 | cubic meters | $m^3$ |
| | | **TEMPERATURE (exact)** | | |
| °F | Fahrenheit temperature | 5/9 (after subtracting 32) | Celsius temperature | °C |

*1 in ≡ 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.


## Approximate Conversions from Metric Measures

| Symbol | When You Know | Multiply by | To Find | Symbol |
|---|---|---|---|---|
| | | **LENGTH** | | |
| mm | millimeters | 0.04 | inches | in |
| cm | centimeters | 0.4 | inches | in |
| m | meters | 3.3 | feet | ft |
| m | meters | 1.1 | yards | yd |
| km | kilometers | 0.6 | miles | mi |
| | | **AREA** | | |
| $cm^2$ | square centimeters | 0.16 | square inches | $in^2$ |
| $m^2$ | square meters | 1.2 | square yards | $yd^2$ |
| $km^2$ | square kilometers | 0.4 | square miles | $mi^2$ |
| ha | hectares (10,000 $m^2$) | 2.5 | acres | |
| | | **MASS (weight)** | | |
| g | grams | 0.035 | ounces | oz |
| kg | kilograms | 2.2 | pounds | lb |
| t | tonnes (1000 kg) | 1.1 | short tons | |
| | | **VOLUME** | | |
| ml | milliliters | 0.03 | fluid ounces | fl oz |
| l | liters | 2.1 | pints | pt |
| l | liters | 1.06 | quarts | qt |
| l | liters | 0.26 | gallons | gal |
| $m^3$ | cubic meters | 35 | cubic feet | $ft^3$ |
| $m^3$ | cubic meters | 1.3 | cubic yards | $yd^3$ |
| | | **TEMPERATURE (exact)** | | |
| °C | Celsius temperature | 9/5 (then add 32) | Fahrenheit temperature | °F |



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# 1. INTRODUCTION

## 1.1 Background

In February, 1979 a Memorandum of Understanding (MOU) was established between the United States Department of Transportation/Federal Aviation Administration (FAA) and the Federal Republic of Germany Ministry of Research and Technology (BMFT) to develop, modify, test and evaluate systems, procedures, facilities and devices to meet the needs for safe and efficient air navigation and air traffic control. Based on this Memorandum of Understanding, Task 1 was defined to assess "the operational requirements for and benefits of 360 degree navigation guidance in the terminal maneuvering area (TMA) and as an integral element of the Time Reference Scanning Beam Microwave Landing System (MLS)." The primary objective was to define the operational and functional requirements for this navigation service without reference to the use of any particular candidate system. A work plan was developed by FRG and FAA representatives to establish these requirements based on a converging set of activities that included selecting TMA geometries(1), agreeing on assumptions of avionics capabilities, and defining the methodology and criteria to assess benefits from a particular level of navigation accuracy.

In the early stages of this activity, the FAA inputs identified several special situations where the use of the MLS/360 degree azimuth function would likely provide benefits; e.g. off-shore oil operations, small remote airfields and airports with special obstacle avoidance/noise abatement problems. On the other hand, the BMFT work was oriented towards the broader concern of determining the role of improved accuracy in the TMA. It was agreed that this broader context was satisfactory for the joint work program, as it would lead to a better understanding of FAA/BMFT views, rather than what could be achieved through work on complementary, but essentially independent studies.

## 1.2 Rationale for Analysis

In controlled airspace around the airports, the controllers presently plan and control traffic manually, and aircraft without area navigation (RNAV) capability are typically vectored to the final approach. Area navigation provides the aircraft an ability to navigate from TMA entry fixes to touchdown without vectoring. During light traffic periods, or where there is no requirement for capacity, the aircraft can navigate using basic RNAV (i.e. 2 waypoint) capability with no need for controller intervention. A controller simply monitors the aircraft

performance, and unless an aircraft grossly blunders, the ATC system can tolerate large aircraft deviations from the intended flight plan. However, during heavy traffic, the controller has to maintain a maximum flow rate to minimize airborne delays while ensuring safety. This controller task is most demanding at the merge points, and in order to minimize the problems of merging traffic, large aircraft deviations cannot be tolerated by the ATC system. Therefore, in current ATC operations, the controllers rely more on the tactical control of aircraft as compared to the long range strategic planning. Vectoring (rather than navigation over predefined fixed paths between waypoints) is used because the controller's ability is limited to precisely plan, control and merge traffic approaching from different directions. Improvements in any one of the elements of ATC (e.g. navigation, surveillance, communications or control) may not readily show any benefits unless some level of ground system automation aids the controllers in planning.

There are efforts underway to develop automation aids to help the controllers efficiently plan the traffic flow. Also, with increasing number of aircraft becoming equipped with sophisticated avionics (flight management computers), the aircraft can fly optimal profiles based on air derived information. With these increased automation aids on the ground and in the cockpit, it has been claimed that higher navigation accuracy could offer the potential to increase capacity. Therefore, at a working group meeting between FAA and FRG representatives, it was agreed to investigate the benefits and requirements for the navigation function making the necessary, but realistic assumptions, regarding ATC automation, traffic environment, and airborne capability. The agreed principal measure of system performance is runway capacity assessed on the basis of ATC planning dispersions at the gate or the outer marker. In short, if runway capacity is not improved (through a reduction in the planning dispersion) by an increase in navigation accuracy under these optimistic conditions, further interest in the subject would not be warranted.

### 1.3 ATC Environment and Assumptions

The ATC system parameters, levels of uncertainties and the performance criterion mutually agreed upon at the meeting with FRG are contained in Appendix A. The assumptions are based on an automated ATC planning and control system assisting the controllers. Currently at even major U.S. airports there is a wide mix of aircraft in terms of avionics capabilities. However, in order to simplify the analysis and bound the

navigation performance requirements, a homogeneous aircraft environment is assumed.

## 1.4 Report Content

In the description of Task I of the MOU, it is specified that the results of the technical investigations should be presented in terms of operational and functional requirements. The operational requirements are qualitative in nature, while the functional requirements represents the quantitative requirements. The methodology for developing these requirements is discussed in Section 2.

A comprehensive set of operational requirements (OR) relating the capabilities of the navigation system and its use in the ATC environment are presented in Section 3. These ORs were developed by modifying the operational requirements for MLS given in Reference 2, on the basis of the assumed ATC environment (Appendix A) in which the new navigation system is likely to provide service to the aircraft. The operational requirements are described in the ICAO format[(2)], because the presentation of ORs in this concise and established form is expected to be useful to the international readers.

The functional requirements for a navigation system are established by quantifying the coverage, accuracy and channel capacity parameters and are presented in Section 4. An approach for selecting the TMA geometries that could derive benefits from the accurate guidance in TMAs was presented in Reference 1. Based on the evaluation in that report, and on an agreed set of assumptions regarding the future ATC operational environment and avionics capabilities discussed in Appendix A, the existing procedures at Chicago O'Hare, and San Francisco International Airports were analyzed to establish the range and accuracy requirements.

In developing the accuracy requirements, a statistical approach is used based on the RSS (root sum square) method of combining impact of various error sources for the worst-case situations. From the analytical results presented in Appendices B, C, and D, functional requirements are quantified and are presented in Section 4. Appendix D contains a simple evaluation of the navigation system's channel capacity, i.e., how many aircraft can make a simultaneous use of the navigation service in a terminal maneuvering area.

## 1.5 Summary

Though the initial intent of this work was broader, the operational and functional requirements defined in this report only consider the general applications of station reference terminal based navaids (e.g., VOR/DME, DME based Azimuth system or DAS) and do not include the special cases noted above.

In IFR meteorological conditions, and potentially in the future at peak hours, the traffic might tend to be generally homogenous consisting of mostly air carrier operations at major airports. Also note that the need for a highly accurate navigation service is only relevent to airports desiring an increase in flow rate i.e., a potential decrease in ATC planning dispersions from $\pm 26$ to $\pm 10$ seconds ($2\sigma$). Thus, the functional requirements presented here would suit the need for a possible future ATC environment in high traffic density terminal areas where increasing capacity may be helped by more effectively using an enhanced navigation system capability.

The analytical results of a scenario based on the procedures and geometry of Chicago O'Hare and San Francisco lead to the conclusion that the use of the assumed delay fan type path control in an automated ATC system would permit the desired gate delivery accuracy of $\pm 10$ seconds ($2\sigma$) to be achieved with the present VOR/DME accuracy and station arrangement. Further, for a scenario based on only speed control over fixed paths, no significant difference in gate delivery performance can be expected between the existing VOR/DME capability and a highly accurate navaid at the airport, such as the DAS which is under development in the FRG.

Finally, it is worth emphasizing that the results presented here using an approach based on single aircraft analysis, provide an adequate evaluation of the navigation system functional requirements. This is because, the results [3] obtained to evaluate the impact of improved navigation accuracy of MLS in an automated metering and spacing environment using a similar single aircraft analysis approach, were later confirmed through fast and real time simulation studies[4] (using a multi-aircraft environment with cockpit simulators and the same system parameters assumed in the analysis) conducted by NASA-Langley Research Center.

## 2. METHODOLOGY

This section contains a description of the methodology and references used in the development of the operational (i.e. qualitative) and functional (i.e. quantitative) requirements for the 360° Azimuth function providing TMA navigation. The operational requirements were developed from the assumptions agreed to with the working group in the Federal Republic of Germany (Appendix A), the operational requirements described in Reference 2, and the general navigation interface requirements with the ATC.

The functional requirements were derived from an analytical model of the ATC environment and primarily relate to coverage, accuracy, and channel capacity. The minimum coverage (range) requirements for an airport was obtained by measuring the radial distance from the airport to the farthest TMA arrival fix, and then adding to it the components of deviations due to navigation along the radial, plus a distance margin needed to transition from the enroute into the TMA.

For accuracy analysis, it was agreed that initially the analysis should consider the overall ATC operation in the TMAs and be constrained to the use of existing procedures at particular airports as opposed to the development of new procedures. In order to isolate the impact of navigation performance from other ATC considerations in planning and execution (e.g., winds, speeds, surveillance errors and communication delays), as a first step, a sensitivity analysis was performed relating the navigation system parameters with the aircraft capabilities to navigate over the desired paths. A detailed error analysis included the impact of navigation in an overall ATC environment.

The general approach to the analysis was based on evaluating the worst-case performance of a single aircraft under a set of assumed ATC uncertainties, and estimating the dispersions in the times of arrival due to the navigation system. The approach is based on a realistic interrelationship between the airport geometry, location and performance capabilities of navaids, and the existing standard operating procedures.

The channel capacity was estimated by evaluating the maximum number of aircraft at Chicago O'Hare that could be simultaneously using the navigation service. The maximum number of aircraft that could be present at any time was obtained from the landing capacity on parallel approaches and the expected

flying time from the TMA entry fixes to touchdown, assuming no gaps in the arrival stream. Then adding to it the number of departure aircraft that could be present in the TMA flying time period, at a rate of one aircraft every minute for a single departure runway.

## 3. OPERATIONAL REQUIREMENTS

The operational requirements for a 360 degree navigation service for terminal areas are specified in this section. These requirements are based on the existing U.S. operating procedures for air carrier operations. It is recognized that any new navigation service should be adaptable to new operating procedures, and also include service to general aviation aircraft without impeding the expected performance. The requirements are based on the assumptions presented in Appendix A and are presented in similar format to the OR contained in Reference 2. It is worth emphasizing here that, in order to obtain the anticipated maximum benefits from accurate navigation, it may be necessary to restrict operations during peak traffic to homogeneous traffic.

### 3.1 General

These requirements are applicable to a high integrity navigation function for providing navigation, missed approach and holding (if needed) guidance:

1. at high density airports;

2. with simplified versions of air and ground equipment for limited operations, but with a system design to permit compatability between all versions of the air and ground equipment.

Commentry on Paragraph 3.1

The navigation service is intended for guidance in high density TMAs with homogenous traffic. During peak traffic conditions advanced avionics capability can be required as the "price of admission". However, during nonpeak traffic conditions the navigation service must be available to aircraft with simplified avionics.

### 3.2 Safety

The navigation system must assure a degree of protection against failures or malfunctions sufficiently high to prevent jeopardizing the safety of flight.

### 3.3 Reliability

The new guidance system shall provide a continuous service and the system design must preclude failures that result in

erroneous data for operationally significant time periods. Any unscheduled break in continuity of service or the radiation of false information shall be sufficiently short or rare as not to affect the safety of aircraft using the system.

Commentary on Paragraph 3.3

Time periods greater than 5 to 10 sec have been suggested as those in which erroneous data may be operationally significant. However, specific figures should be defined when the future flight control system characteristics are identified.

## 3.4 Integrity

Automatic positive indication of any failure to meet the overall specification shall be given to the aircraft and, when the ground element is involved, also to Air Traffic Control (ATC).

Commentary on Paragraph 3.4

ICAO Annex 10, para. 3.1.1 defines integrity as "that quality which relates to the trust which can be placed in the correctness of the information supplied by the facility". In this Operational Requirement, the interpretation of integrity is extended to cover the correctness of information provided in the aircraft by the service.

## 3.5 Aircraft Types

The system shall be capable of being used by all Conventional Take-Off and Landing (CTOL) and Short Take-Off and Landing (STOL), propeller or turbo-jet aircraft likely to be operating during the foreseeable life of the navigation system. The system must also provide services to Vertical Take-Off and Landing (VTOL) aircraft, including helicopters, when operating within the limits of the coverage of the system.

Commentary on Paragraph 3.5

The recommended accuracy requirements presented in the next section are based on an all air carrier operations with similar speed profiles and avionics (e.g., RNAV, INS and accurate autopilot) capabilities. In peak traffic, even though the impact of navigation is less dominant than other ATC uncertainties, the navigation ability of other users should not be a limiting factor that could impact the overall ATC performance.

## 3.6 Range of Aircraft Speeds and Attitudes

The guidance information provided in an aircraft shall not be affected significantly by variations in aircraft speed and attitude.

Commentary on Paragraph 3.6

The aircraft speed assumed are 250 knots (upper limit) at arrival fix and 150 knots at the gate along the extended centerline of the runway in use.

## 3.7 Air Traffic Control Considerations

The system should not be the limiting factor in achieving the maximum operationally acceptable movement rate (capacity) at an airport. There should also be an adequate overlap at the interface with en route navigational facilities to ensure an efficient transition to the terminal maneuvering areas.

TMA maneuvers outside the coverage of the new guidance system will make use, as necessary, of other navigational aids (VOR, DME, etc.). Within the coverage of the new guidance system these other navigational aids may also be available. The new navaid should provide for a smooth transition to and from the use of these en route aids during manual flight and when automatic flight control systems are in use, as well as with the landing aid, viz MLS, if also used to provide guidance in some segments of the TMA.

Commentary on Paragraph 3.7

It is recognized that a computer aided terminal area surveillance system will be needed to accomplish aircraft scheduling and sequencing in order to achieve a high runway acceptance rate. The guidance provided by the new system should be of such quality as to permit the aircraft to make good a designated flight path without reliance on other systems.

In order for the navigation system not to be a limiting factor in achieving high flow rate, the system providing guidance to the aircraft in TMAs should be able to support $\pm 10$ seconds $(2\sigma)$ individual aircraft landing or $\pm 16$ seconds $(2\sigma)$ interarrival accuracy.

## 3.8 Meteorological Considerations

The system coverage and the quality of the guidance information shall not be affected to an unacceptable degree by meteorological conditions.

## 3.9 Guidance Presentation

3.9.1 The interf e between man, the machine and the associated procedures shall be geared toward simplicity and standardization.

3.9.2 Airborne receiver/processor will provide outputs which will be directly usable by current and future guidance and control systems, and displays. These outputs will be analog and/or digital and will consist of both basic functional data and computer functions based on these data.

3.9.3 The aircraft system shall be capable of providing an acceptable and unmistakable warning to the pilot of inadequate, false or ambiguous information.

3.9.4 The system should provide signals which are readily adaptable for use by existing aircraft instruments and automatic flight control systems.

## 3.10 Airborne Monitoring

When the airborne monitor system senses that the system operation is erroneous, it shall cause appropriate alarm, or caution messages, or warnings (e.g. flags) to be displayed. The monitoring functions provided should interface with appropriate displays and flight control equipment.

### Commentary on Paragraph 3.10

As shown in Appendix C, for maximum capacity related benefits from navigation service, the ATC system would have to assume full responsibility of the aircraft in case of navigation failure. As such, stringent airborne monitoring requirements would be needed to warn the pilots, as well as the ATC system, to take some action for safety of the aircraft.

## 3.11 Classes of Service

3.11.1 The guidance service shall be available in a modular form so that the class of service appropriate to the differing requirements of airport and aircraft operators respectively can be provided. The guidance service shall be capable of meeting

the needs of dense, complex traffic patterns at major airports having multiple runways, including closely spaced parallel runways. The least complex airborne installation shall be capable of operating with the most complex ground installation with a resulting capability no less than that of the airborne installation.

Commentary on Paragraph 3.11.1

Even though the navigation accuracy is only important in TMAs desiring to increase capacity or safety (i.e. by reducing holding pattern airspace requirements close to the airports, when applicable), the navigation system design shall provide usable navigation service to users with less capability during nonpeak traffic periods.

3.11.2 The system should provide continuous azimuth and distance information to all types of aircraft during flights from TMA entry fixes to the final approach fix (e.g., outer marker), missed approaches and holdings (if employed).

## 3.12 Siting Of Ground Equipment

3.12.1 The ground elements of the navaid shall be capable of being sited so as not to conflict with aircraft movement while providing continuous coverage to the aircraft being served.

3.12.2 The inherent performance of the system shall be such that siting of the ground facility is essentially independent of near and far field terrain effects and the effects of elements such as airport structures, moving or stationary ground vehicles and aircraft.

3.12.3 It is essential that the equipment arising from this OR co-exist without causing interference to any ICAO standard radio navigation and communication system.

## 3.13 Flight Inspection

The inherent performance of the system shall be such that the operational and technical need for in-flight calibration and inspection will become unnecessary except for the initial commissioning of the facility.

### 3.14 System Channel Capacity

The system shall be capable of providing the specified guidance information to the maximum number of aircraft that can be expected to use the system simultaneously.

### 3.15 Maintenance

The inherent design of the system shall be such that the need for maintenance is reduced to a practical minimum.

# 4. FUNCTIONAL REQUIREMENTS

The functional requirements stated in this section are derived for the most part of the TMA operation, i.e., to permit the aircraft to navigate only over fixed paths between waypoints, and to arrive at the final approach fix with an error that is negligible when compared with other ATC errors. An aircraft receives distance and azimuth information from the ground, and the onboard flight control system using this information maneuvers the aircraft to the appropriate positions in space. The navigation system requirements specified in this section are for guidance in the horizontal plane. The altimeter provides the vertical information. In order to achieve the maximum airport flow rate or capacity, the aircraft deviations from the intended tracks should be minimized. These deviations depend upon the accuracy of the range and azimuth information, and the ability of the flight control system to maintain the intended flight paths. The key functional requirements specified in this section are coverage, accuracy, channel capacity and others from the ICAO Reference 2. The rationale for the quantification are defined in Appendices B, C and D.

## 4.1 Coverage (Range) Requirements

Based on the current requirements at major U.S. airports, the navigation system shall provide distance and azimuth information to the aircraft within a 50 N.MI. radial distance from the airport. (See Appendix B).

## 4.2 Accuracy Requirements

### 4.2.1 Azimuth Accuracy

The $2\sigma$ azimuth accuracy is $\pm$ 0.6 degrees (see Appendix C) for a navaid located at the airport. The accuracy is $\pm 1.7^{o}$ ($2\sigma$) for navaids located elsewhere in the TMA. At the airports where capacity is not a requirement, or the aircraft do not use RNAV along the entire route, an azimuth accuracy of $\pm 3.9^{o}$ ($2\sigma$) is adequate.

The $2\sigma$ flight technical error in maneuvers should be $\pm$ 1200 ft.

Commentary On Paragraph 4.2.1

The results in Appendix C show that with the existing procedures at U.S. airports, some path control will be needed virtually independent of the navaid accuracy, and once path control is

employed, improvements in navaid accuracy has no impact on capacity related parameters. However, in the future, with en route automation and more aircraft getting equipped with flight management systems, improvements in navigation accuracy of the level cited above, can help reduce path control, and lead the ATC towards achieving the desired capacity related objectives. Such a concept would tend towards transfering control into the cockpit thereby reducing controller workload through the use of airborne derived commands.

### 4.2.2 Distance Measurement (Range) Accuracy

For the 360 degrees coverage system, the $2\sigma$ distance (range) measuring accuracy (within a 50 N.MI. radial distance around the airport) of $\pm$ 0.14 N.MI. is considered adequate.

## 4.3 System Capacity

The navigation system should be able to provide guidance to 50 aircraft simultaneously (Appendix D).

## 4.4 Ground Monitoring

The monitor should cause radiation to cease if the following deviations from the established conditions arise:

1. a change in excess of 0.4 degree for an airport based navaid and 1 degree for other navaids at the monitor site of the bearing information.

2. a change in excess of 0.4 microseconds for an airport based navaid and 1 microsecond for other navaids in the transponder time delay at the monitor point of the range information.

### Commentary on Paragraph 4.4

The above monitoring deviations are derived from the ICAO requirements for a VOR/DME, by assuming a direct relationship of the monitoring capability to the azimuth/range accuracy of the navigation system. The exact monitor requirements are system and implementation dependent and can only be established by monitoring and testing the actual hardware.

## APPENDIX A

## ASSUMPTIONS FOR ATC ENVIRONMENT

In order to analyze the interaction between navigation and ATC in TMAs to develop the operational and functional requirements, it is essential to establish an ATC environment in which the navigation system is supposed to operate. A set of assumptions defining the elements of ATC system, the avionics capabilities and traffic requirements are presented in this section. These assumptions were jointly developed by U.S. and FRG representatives at a working group meeting in March 1981[5].

### A.1 General Assumptions About TMA Type, Traffic Volume, Mix And Shares Of IFR And VFR

A.1.1 Only TMAs with high traffic volume need to be investigated.

A.1.2 The benefits of improved navigation accuracy would be to improve capacity at existing runways.

A.1.3 There is a tendency towards homogeneity of aircraft during peak hour traffic (homogeneity in the sense of on-board avionics equipment and aircraft performance). It is anticipated that means can be found to accomodate the inhomogeneous part of traffic either on separate runways or during periods of lower traffic volume.

A.1.4 The current IFR separation values are 3, 4, 5, 6 NM between successive aircraft pairs depending on the types of aircraft. It is beyond the scope of this analysis to investigate possibilities for reduction of IFR separation minima, even though it is agreed that a reduction of radar separation minima may have a higher impact on airport capacity than a reduction of the safety buffer from the current $\pm 36$ seconds to $\pm 16$ seconds ($2\sigma$).

### A.2 Control Procedures

A.2.1 It is assumed that some form of en route metering procedures will be available to provide

- Tolerance for arrival over TMA entry fix of $\pm$ 1 minute ($2\sigma$).

- Holding will normally be performed in en route airspace.

A.2.2 Aircraft will in general be assigned predetermined path from arrival fixes to the gate over published waypoints.

- Airspeeds would range from 250 to 160 Knots (IAS).
- For the investigation the gate will be located 7 NM from threshold. The gate is the measuring point for variations of buffer size. From the gate the aircraft will fly a straight in approach without further intervention from the ground.

A.2.3 Both speed and path control procedures can be applied. Path control will be performed in the form of delay fan type procedures.

A.2.4 Altitude control will not be used for spacing aircraft.

A.2.5 Holding in the terminal area will be restricted to emergency cases and for missed approach procedures.

## A.3 Surveillance and Communications

A.3.1 Improved DABS accuracy is not expected to have much impact on overall ATC performance.

A.3.2 Parameters assumed for ground surveillance, communications and control are

- Detection capability $0.25^{\circ}$, 375 feet ($1\sigma$)
- Quantization for speed commands in 10 Knots
- Quantization for time commands negligible.

Data link could help to reduce communication delays only between ground and airborne computers. Communication delays involving pilot and controller reaction times will not be reduced. Data link will help to improve wind forecasts by transmitting INS or Air Data information.

Parameters for communication and wind forecasts:

- Communication delay (time lag between first display of command until first aircraft maneuver

including all transmissions and verifications) 7 seconds ($1\sigma$)
- Errors in alongtrack wind 5 Knots ($1\sigma$)

## A.4 Airborne Capabilities

A.4.1 Aircraft capability and relevant parameters for avionics complement

- Radio navigation
- INS or air data computer
- 2D-RNAV
- Autopilot accuracy during maneuvers ranging from 150 feet to 1500 feet ($1\sigma$).
- Flight management system (FMS)

## Commentary on Paragraph A.4

In order to make an effective use of high navigation accuracy, the aircraft needs sophisticated avionics capabilities e.g., INS, RNAV, and flight management computers, etc. to precisely maneuver aircraft after processing accurate navigation sensor data. Even though the agreed assumptions in Reference 5 did not specifically include flight management capabilities, with the new generation of aircraft (Viz B-757/767) coming out equipped with such capabilities, and most of the airlines retrofitting their fleet with FMS, it is useful to assume the FMS capability in future requirements. A fully automated navigation/thrust management system through interface with INS, optimally use air data, DME slant range and VOR omni bearing information to estimate position. In addition, the FMS performs frequency management and auto tune function to control VOR/DME frequency selection[6], a feature that could minimize pilot workload in situations when multiple navaids are used for guidance.

A.4.2 Aircraft performance data

| | |
|---|---|
| - Transition speed | 250 Knots IAS |
| - Approach speed | 160 Knots IAS |
| - Decelaration rate | 50 Knots/minute |
| - Descent gradient | 300 feet/NM |
| - Turn rate | $1.5^{\circ}$/second ( > 210 Kts IAS) |
| - | $3^{\circ}$/second ( ≤ 210 Kts IAS) |

## A.5 Performance Criterion

Under the assumed ATC environment the desired accuracy for an individual aircraft at the gate is 5 seconds ($1\sigma$).

## APPENDIX B

## ESTABLISHMENT OF RANGE REQUIREMENTS

In the National Airspace System, aircraft typically navigate over VOR radial routes before entering the terminal airspace. With area navigation, the aircraft have the ability to navigate from entry fix to touchdown. The alongtrack deviations of aircraft on straight flight paths can affect the aircrafts' times of arrival at the threshold, thereby reducing runway capacity and inducing airborne delays. When the aircraft fly profiles involving turns, the crosstrack deviations translate into alongtrack deviations, and as such, they also affect arrival times. For an airport-based $(\rho,\theta)$ navigation system, the radial coverage should possibly encompass all sections of STARs (Standard Arrival Routes) where sizable turns (turn angles greater than $15^{o}$) are involved, since at this point crosstrack deviations get translated to alongtrack deviations

With the existing procedures in the U.S., most of the arrival routes within a 100 nmi radial distance from the major airports are generally laid out straight into the terminal arrival fixes, where the aircraft typically make their first turn. The minimum range requirement at any arrival fix for an airport-based $(\rho,\theta)$ navigation system, is obtained by measuring the radial distance from the airport to the fix and then adding to it the components of the alongtrack and the crosstrack deviations along the radial, plus some distance margin for transitioning to the TMA. A 5 nmi distance margin is assumed in this work that corresponds to one minute of flying time at 250 knots IAS and 10,000 feet. At an airport, the largest of the radial distance needed for each arrival fix is selected as the range requirement for that airport.

Table B-1 shows the maximum range requirements at ten major U.S. airports. The table also shows the arrival fix at each airport where this maximum range is required along with the corresponding radial distance and along-the-radial deviations due to guidance from an airport-based navaid. With the exception of range required for the aircraft arriving at the specific fix at San Francisco shown in Table B-1, the range requirements at the other San Francisco fixes and all other airports are within a 50 nmi radial distance from the airport. With this coverage requirement, the aircraft arriving at the Groan fix at San Francisco would have to use enroute navaids. As shown in Appendix C, due to large amount of controllability in the initial segments of flight in the TMA, larger navigation deviations would have no impact on the final performance.

TABLE B-1
RANGE REQUIREMENTS

| AIRPORT | ARRIVAL FIX | RADIAL DISTANCE FROM AIRPORT (N. MI.) | NAVIGATION DEVIATION ALONG THE RADIAL (N. MI.) | STABILIZATION MARGIN (N. MI.) | RANGE REQUIRED (N. MI.) |
|---|---|---|---|---|---|
| CHICAGO (O'HARE) | CHICAGO HEIGHTS | 32.5 | 1.00 | 5.0 | 38.5 |
| NEW YORK (JFK) | MICKE | 33.0 | 1.00 | 5.0 | 39.0 |
| ATLANTA | WOMAC | 23.0 | 0.69 | 5.0 | 28.69 |
| LOS ANGELES | SEAL BEACH | 21.0 | 1.77 | 5.0 | 27.77 |
| SAN FRANCISCO | GROAN | 51.5 | 1.63 | 5.0 | 58.13 |
| DENVER | FLOTS | 19.0 | 0.57 | 5.0 | 24.57 |
| MIAMI | DOLIN | 26.0 | 1.98 | 5.0 | 32.98 |
| DALLAS/FT. WORTH | BRIDGEPORT | 43.0 | 2.46 | 5.0 | 50.46 |
| MINNEAPOLIS | CRAMS | 37.0 | 2.57 | 5.0 | 44.57 |
| WASHINGTON/DULLES | SCOBY | 41.0 | 3.33 | 5.0 | 49.33 |

Consequently, the above coverage requirements can be accepted in relationship to the desired capacity performance. In future, if the aircraft are required to hold at Groan, and tighter airspace limits are desired around the fix, then the range requirements would have to be extended to 60 n.mi. at San Francisco.

## APPENDIX C

## ERROR ANALYSIS TO ESTABLISH ACCURACY REQUIREMENTS

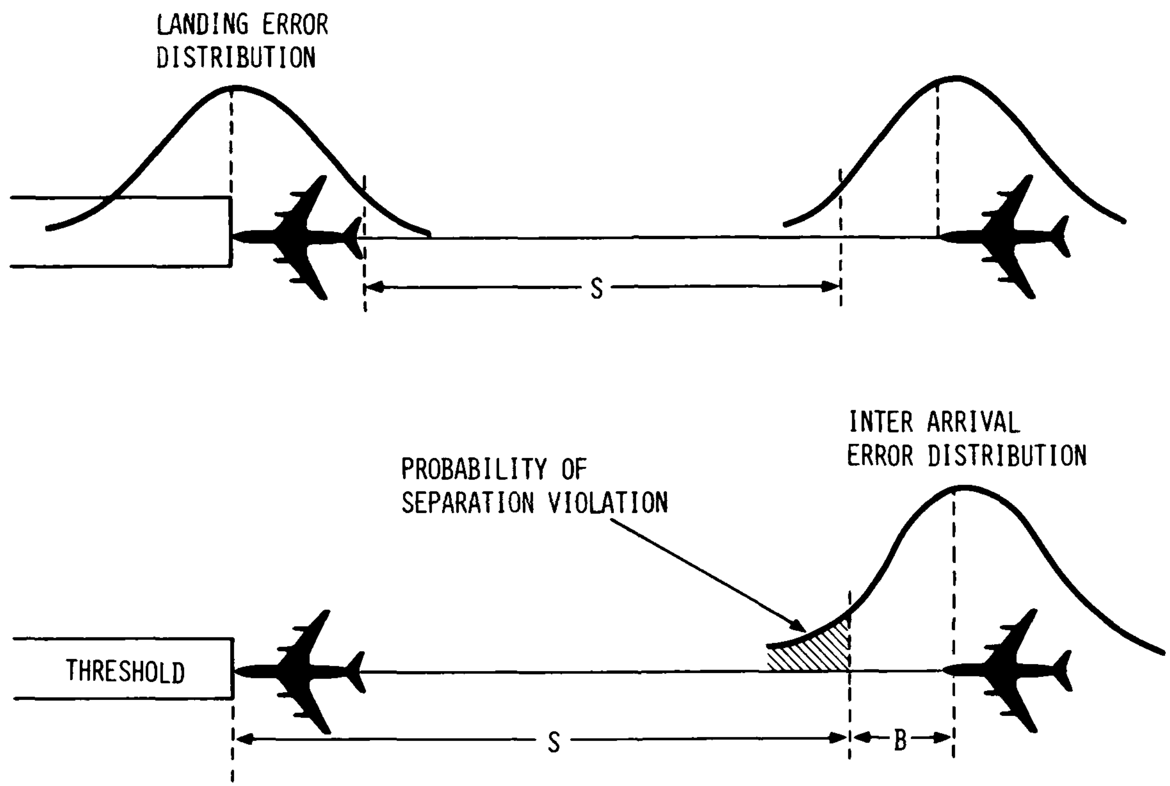
In this section, the results of an error analysis are presented to establish navigation system accuracy requirements in the TMAs. This analysis is based on a single aircraft performance (the aircraft equipped with RNAV and automatic flight control system) and, current route structure and control procedures employed at Chicago O'Hare and San Francisco International airports. The analysis takes into the consideration the relationship between the navigation parameters and other ATC functions used in planning and control of aircraft.

### C.1 Impact Of ATC Uncertainties On Airport Capacity

During high density traffic periods, the ATC system has to plan scheduled landing times and sequence so as to efficiently land aircraft with minimum delays in the TMA without violating the desired minimum separations. In order to maintain a maximum flow rate the key ATC planning and control consideration is to assure that neither are the landing time slots lost nor are there violations of minimum separations. Because of a number of uncertainties in the ATC planning process due to the ground system's inability to know the winds and actual aircraft performance perfectly, the ATC system can only assign landing times on its best estimates of the aircrafts time/distance relationship.

As the flight progresses, the ground system monitors the aircraft performance against its own plan, and issues control actions to correct the deviations between planned vs. actual performance. Due to control limitations, both from the efficiency and controller workload point of view, the aircraft would normally land with some deviations from the ATC projected landing times. When a successive pair of aircraft have landing errors, the planned minimum separation could get larger on actual landing (called a gap), or reduce, thereby causing a violation of the desired separation.

In order to prevent such separation violations, the ATC system has to plan with a protection buffer to cover the uncertainties. The buffer correspond to the cummulative effect of the landing errors of two individual aircraft in succession as shown in Figure C-1. If the landing errors are assumed to be normally distributed, and all aircraft have a similar performance, the interarrival error between a successive pair of aircraft is just 1.41 times the individual error. As shown




S - DESIRED IFR SEPARATION
B - PLANNED BUFFER TO OFFSET UNCERTAINTIES
S+B - PLANNED SEPARATION

**FIGURE C-1**
**PLANNED MINIMUM SPACING BETWEEN AIRCRAFT**

in Figure C-1, the planned separation (S+B) is a measure of capacity. Reducing either of the parameter S or B would increase capacity. This analysis is based on simply evaluating the impact of navigation accuracy on the buffer only. The desired size of the buffer at the gate is based on 5 seconds ($1\sigma$) for a single aircraft or 8 seconds ($1\sigma$) for interarrival error[3,4] between a pair of aircraft.

## C.2 Arrival Geometry

In Reference 1, it was demonstrated that the geometry from Pappi fix to runway 32 at Chicago's O'Hare provides the potential of deriving maximum benefits from an accurate airport based navaid. The arrival geometry from the Stinson Beach fix to runway 28 at San Francisco was considered of interest due to terrain considerations. Based on the understanding of current procedures, an arrival and control geometry was developed for each of the above two cases and is shown in Figures C-2 and C-3 respectively. Even though, in practice the controllers use a trombone approach for vectoring, the above geometries assume delay fan type vectoring procedures as agreed to with the FRG. The speeds and altitudes are reasonably consistent with the current operations.

## C.3 Navigation System Accuracy

A parametric analysis is performed to investigate the effect of navigation accuracy on ATC performance while satisfying a gate delivery accuracy requirement of $\pm 10$ seconds ($2\sigma$). The accuracy parameters considered for each function are listed in Table C-1. As shown in the table, the VOR/DME range and azimuth accuracies are considered for an aircraft with a general receiver and with an ARINC quality receiver. DAS like system accuracy[7] is considered for an airport based navaid. The following seven navigation configurations, based on navaid accuracies and locations, were analyzed in this study.

1. The aircraft with minimum performance general VOR/DME receivers get guidance from the navaids at current locations.

2. The aircraft with minimum performance general VOR/DME receivers get guidance from a single navaid located at the airport.

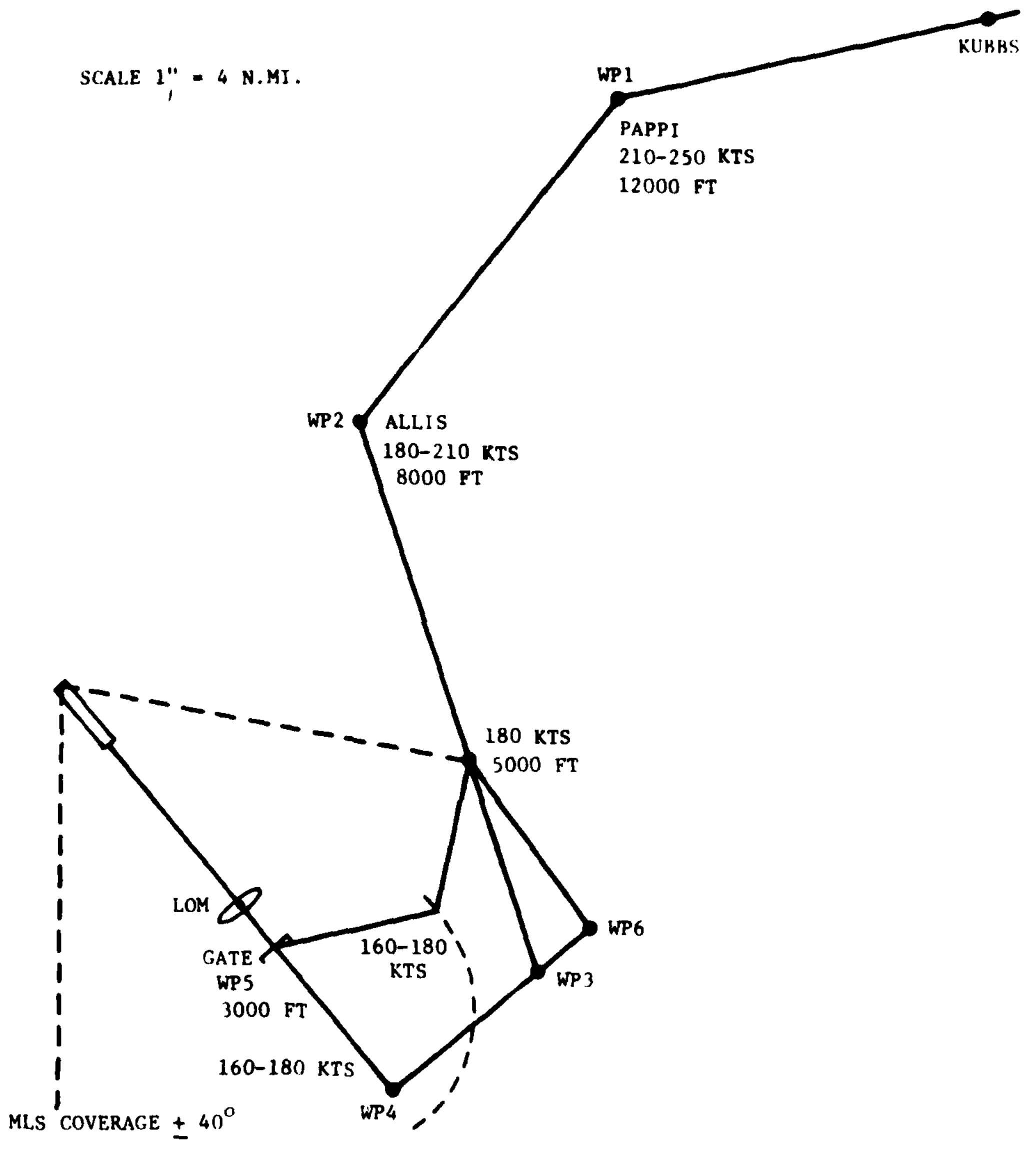



**FIGURE C-2**
**CHICAGO O'HARE ARRIVAL AND CONTROL GEOMETRY**
**(FOR RUNWAY 32)**

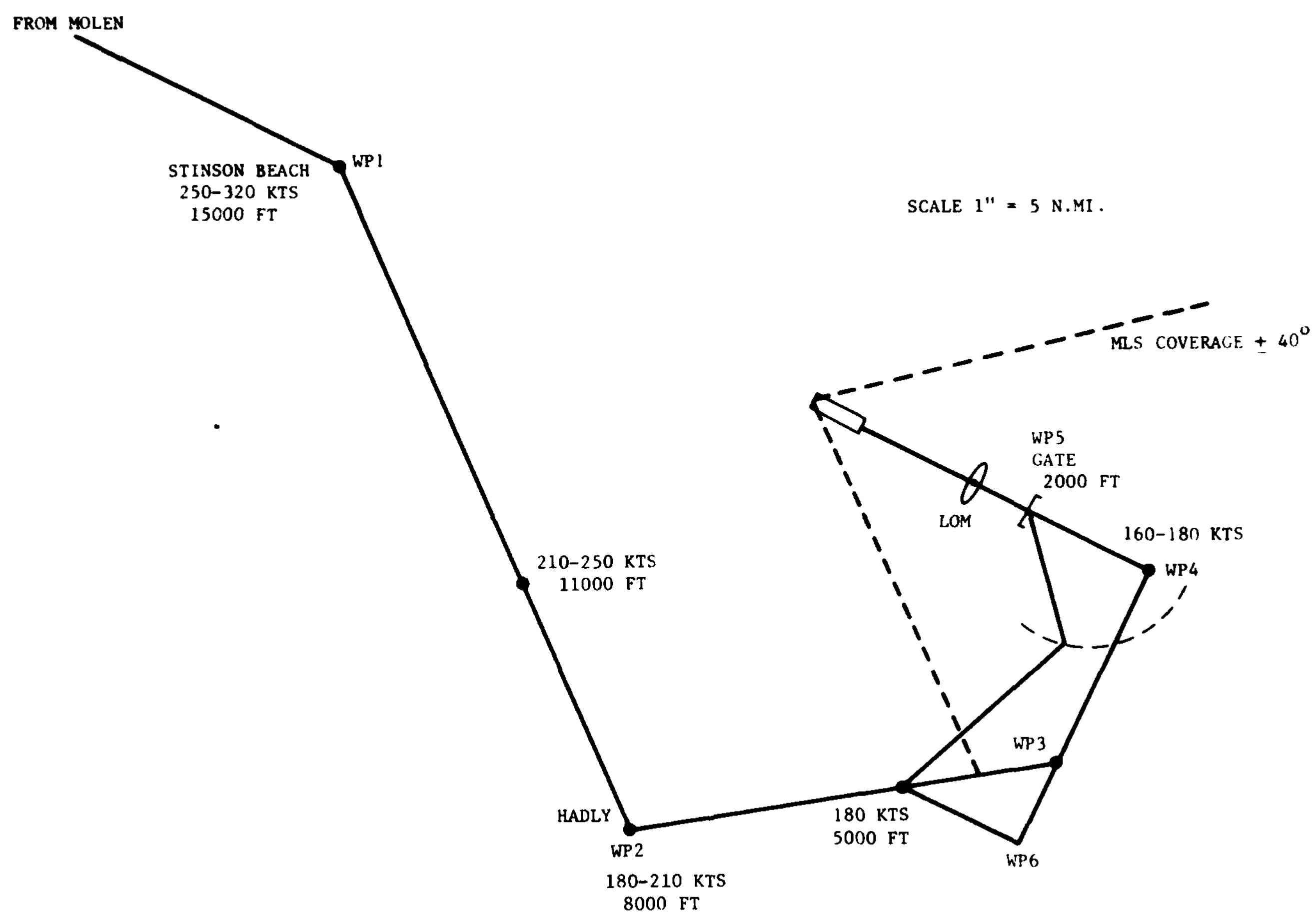



**FIGURE C-3**
**SAN FRANCISCO ARRIVAL AND CONTROL GEOMETRY**
**(FOR RUNWAY 28)**

TABLE C-1
NAVIGATION SYSTEMS ERROR BUDGET

| Navaids | Aircraft | Navigation System Parameter | Error Component | $\pm 2\sigma$ Error |
|---|---|---|---|---|
| Existing | General | Azimuth | Ground Station | 1.4° |
| | | | Airborne Receiver | 3.0° |
| | | | Course Selection | 2.0° |
| | | | Total | 3.87° |
| | | Range | Total | 0.2 + 1% of $\rho$ N.M. |
| Existing | Air Carriers | Azimuth | Ground Station | 1.4° |
| | | | Airborne Receiver | 1.0° |
| | | | Course Selection | Negligible |
| | | | Total | 1.72° |
| | | Range | Ground Station | 0.1 N.M. |
| | | | Airborne Receiver | 0.1 N.M. |
| | | | Total | 0.14 N.M. |
| A Highly Accurate Airport-Based Navaid Like DAS(7) | Air Carriers | Azimuth | Total | 0.1° |
| | | Range | Total | 100 Ft. |

3. The aircraft with air carrier ARINC quality (high performance) VOR/DME receivers get guidance from the navaids at current locations.

4. The aircraft with air carrier ARINC quality (high performance) VOR/DME receivers get guidance from a single navaid located at the airport.

5. The aircraft with air carrier ARINC quality (high performance) VOR/DME receivers get guidance from the navaids at current locations outside the MLS coverage, and the MLS provides guidance within $\pm 40^{\circ}$ coverage.

6. The aircraft get guidance from a single navaid located at the airport with an overall azimuth accuracy of $\pm$ 0.1 degree ($2\sigma$) corresponding to the DAS type system but having a range accuracy of $\pm$ 0.14 n.mi. ($2\sigma$) based on air carrier ARINC quality DME receivers.

7. The aircraft get guidance from a single navaid (like DAS) located at the airport with an azimuth accuracy of $\pm 0.1^{\circ}$ ($2\sigma$) and a range of $\pm$ 100 Ft. ($2\sigma$).

The MLS accuracies were determined by a linear interpolation of the recommended accuracies in Reference 2 for a given range and angular position of the aircraft.

$$\text{Range accuracy } (\pm 2\sigma) = 300 + 69.23\,(\rho - 7) \text{ ft.} \qquad \text{(C-1)}$$

$$\text{Azimuth accuracy } (\pm 2\sigma) = \frac{1146}{R}\left(1 + \frac{\theta}{80}\right)\left(1 + \frac{\rho}{20}\right) \text{ degrees} \qquad \text{(C-2)}$$

Where

$\rho$ - Range of aircraft in N.Mi.

$\theta$ - Angular position of aircraft w.r.t. runway centerline

R - Runway length in feet.

## C.4 Impact Of Navaid Accuracy And Locations On Aircraft Arrival Times At The Outer Marker

### C.4.1 Derivation Of Cummulative Time Errors

Based on the ( $\rho$, $\theta$ ) navigation system accuracy, an aircraft could be located anywhere within a rectangular space around each turn point as shown in Figure C-4, when the desired position is at the center of the rectangle. For the analysis the sides of the rectangle are assumed to be equal to $\pm 2\sigma$ alongtrack and crosstrack deviations. To simplify the analysis, worst-case conditions are considered where the aircraft navigates along the longest or the shortest paths as shown by the dotted lines in Figure C-4. The difference between the lengthened or the

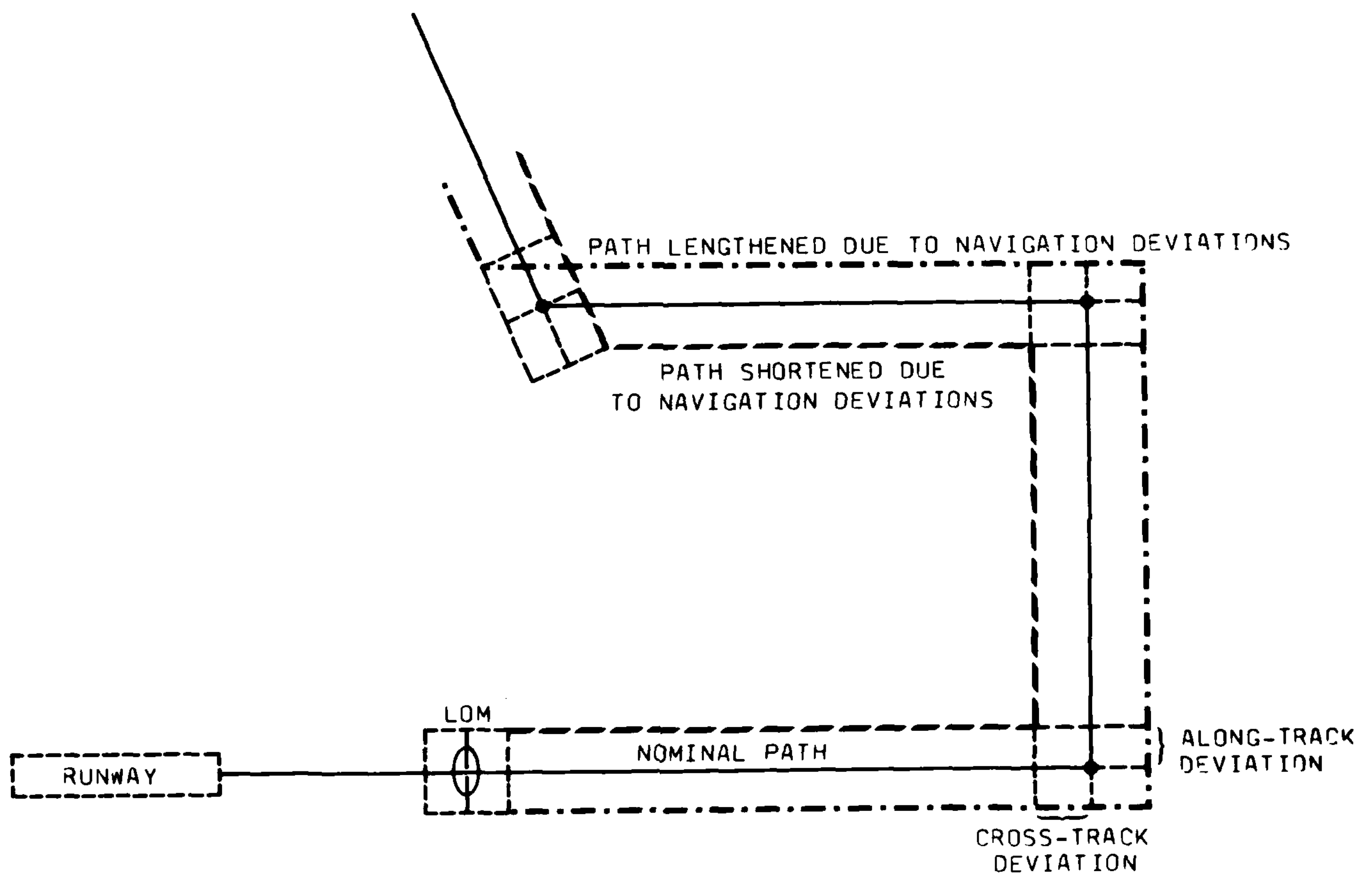



**FIGURE C-4**
**IMPACT OF DEVIATIONS DUE TO NAVIGATION ON THE FLIGHT PATH TO OUTER MARKER**

shortened path and the nominal path is the distance deviation due to navigation under worst-case situations. This distance deviation could affect the time of arrival at the outer marker depending upon the aircraft's speed. The deviations for two aircraft in-trail on the final approach could adversely affect the desired interarrival spacing which relates to capacity.

The worst-case distance deviations over a flight path shown in Figure C-4, is determined by computing the alongtrack and the crosstrack deviations at each turn point and the outer marker. The relationship between the alongtrack and the crosstrack deviations for an RNAV equipped aircraft, the location of turn point with respect to the navaid (i.e., distance and the angle of intersection between the radial from the ground station and the track), and the accuracies of ($\rho,\theta$) navigation system is presented in Reference [8] and is reproduced below for ready use.

The elements of navigation errors considered in the analysis are:

1. Crosstrack Error ($\sigma cc$)
2. Alongtrack Error ($\sigma ac$)
3. Flight Technical Error ($\sigma p$)

For a rho/theta system the crosstrack and alongtrack standard deviation equations are as follows:

$$\sigma cs = \sigma d\ [1 + (E^2-1)\ Cos^2A]^{1/2} \qquad (C-3)$$

$$\sigma as = \sigma d\ [1 + (E^2-1)\ Sin^2A]^{1/2} \qquad (C-4)$$

where

$\sigma cs$ = Crosstrack error standard deviation due to sensor
$\sigma as$ = Alongtrack error standard deviation due to sensor
$\sigma d$ = Standard deviation of the errors of distance determination

$E = \dfrac{D\ \sigma\theta}{57.3\sigma d}$ (Ratio of VOR azimuth to range error standard deviation) (C-5)

D = Distance from ground station to the aircraft on the course line of interest
$\sigma\theta$ = Standard deviation of the errors of bearing determination in degrees
A = Acute angle of intersection of the radial from the ground station and the course line

The crosstrack error standard deviation at a turn point is defined as

$$\sigma cc = a \sqrt{\sigma cs^2 + \sigma p^2} \qquad \text{(C-6)}$$

where

$a$ = 0.7 (obtained from the simulation results[9] and is due to the filtering of high frequency noise components)
$\sigma p$ = Standard deviation of flight technical error

The flight technical error is not included in the alongtrack errors[3], and hence

$$\sigma ac = \sigma as \qquad \text{(C-7)}$$

The worst-case cummulative time error at the outer marker due to $2\sigma$ navigation errors is given by

$$\sigma tim = \frac{1}{v1} (\sigma cc_1 \ Sin\alpha_1 - \sigma ac_1 \ Cos\ \alpha 1) + \sum_{k=2}^{n} \frac{\sigma ack}{vk}$$

$$+ \sum_{k=2}^{n-1} \frac{1}{vk} (\sigma cck \ Sin\alpha k + \sigma ack \ Cos\alpha k) \qquad \text{(C-8)}$$

where

$\sigma ac_k$ - Alongtrack standard deviation at the kth turn point
$\sigma cc_k$ - Crosstrack standard deviation at the kth turn point
$\alpha\kappa$ - Included angle at the kth turn point
$\sigma tim$ - Cummulative time error
vk - Ground speed at the kth turn point

## C.4.2 Navigation Error Sensitivity Analysis Results

The worst-case navigation (i.e. neglecting the surveillance, communication, ATC planning and arrival fix errors for the time being) induced cummulative time errors at the outer marker as a function of flight technical errors for the seven navigation configurations listed earlier, are illustrated in Figure C-5 for Chicago O'Hare, and in Figure C-6 for San Francisco. The figures show that the flight technical error begins to dominate as the navigation system becomes highly accurate. If one assumes that the flight technical error also gets reduced with

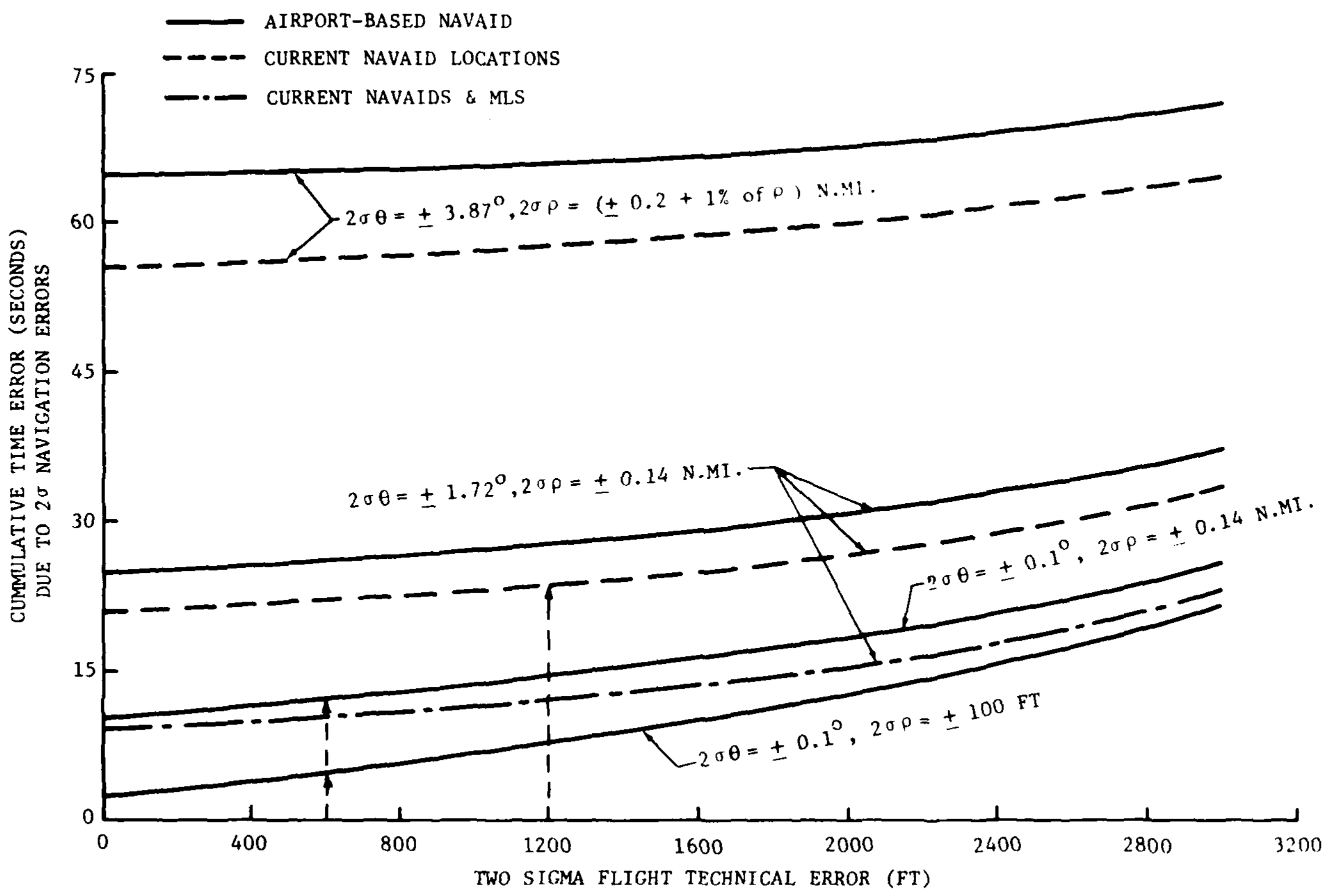



**FIGURE C-5**
**WORST CASE NAVIGATION INDUCED ERRORS AT THE OUTER MARKER AS A FUNCTION OF FLIGHT TECHNICAL ERROR (CHICAGO O'HARE RUNWAY 32)**

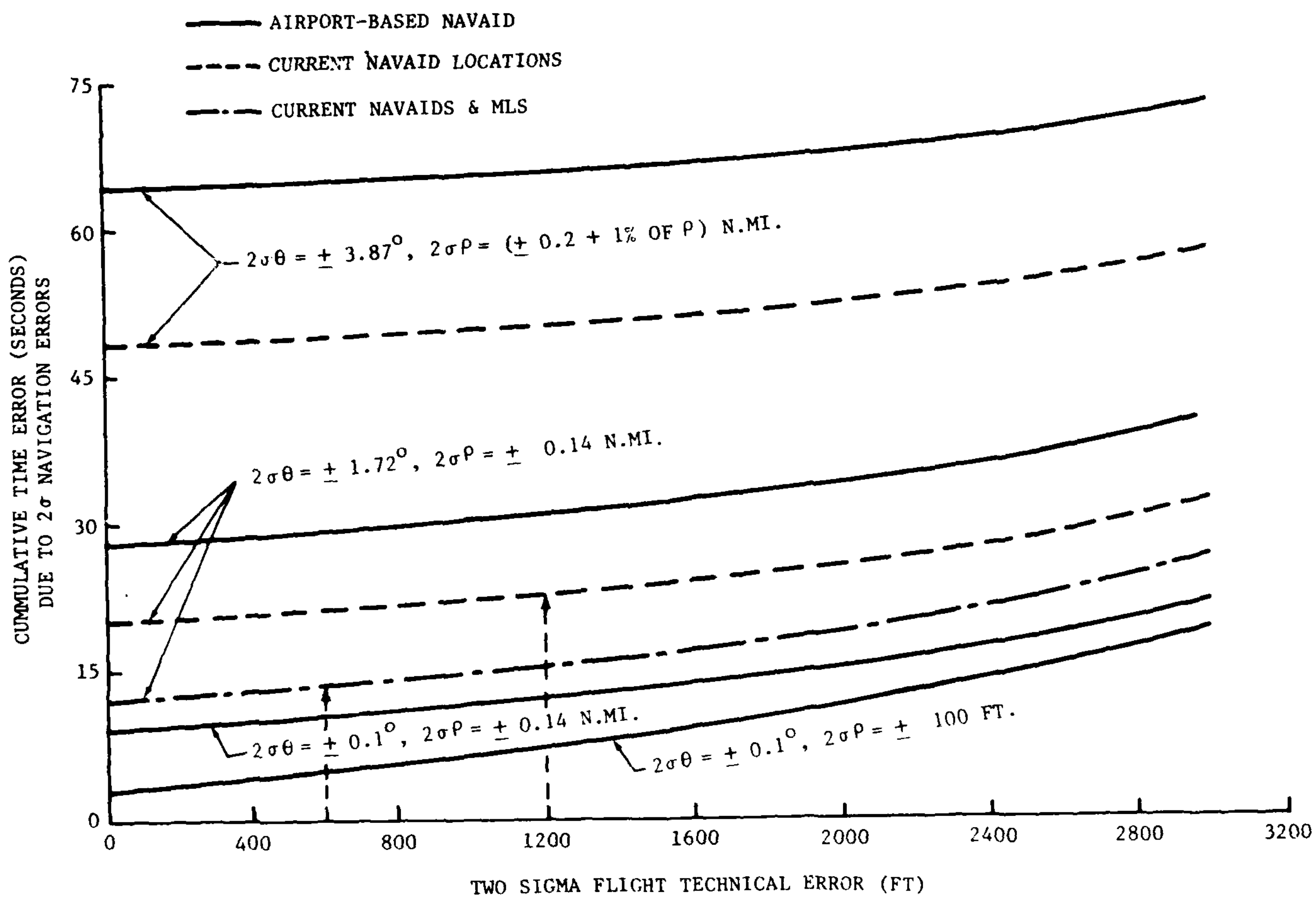



**FIGURE C-6**
**WORST CASE NAVIGATION INDUCED ERRORS AT THE OUTER MARKER AS A FUNCTION OF FLIGHT TECHNICAL ERROR (SAN FRANCISCO RUNWAY 28)**

the increase in navaid accuracy, the above figures indicate a comparison of performance with two example scenarios. The performance of the air carriers using current navaids and having a flight technical error of ± 1200 ft ($2\sigma$) is compared to the navigation performance of the aircraft using a highly accurate navaid at the airport (e.g. DAS) and having a flight technical error of ± 600 ft ($2\sigma$). The navigation performance does improve somewhat with a high azimuth accuracy system. The navigation performance does improve significantly with a highly accurate range and azimuth system, although when an MLS is used in conjunction with the existing navaids, the performance differences are not very large. In any case, it will be demonstrated in the next section that the impact of navigation errors with the above two scenarios on an overall ATC system performance is not significant because the other system uncertainties (speeds and winds) dominate the total error budget.

## C.5 Evaluation Of Final Delivery Errors And Controller Workload

### C.5.1 Aircraft Deviations And Control

As discussed earlier, during peak traffic the ground system has to efficiently plan the aircrafts' scheduled landing times to keep a high flow rate. Due to uncertainties in the estimation of aircrafts' ground speed (i.e. due to IAS and wind errors), the aircrafts' actual times of arrival at different points along the route deviate from the ground system projected times. Such deviations increase with the distance flown. Consequently, the control function in ATC must change the aircrafts' flying time in accordance with the desired landing time by either changing its speed or the path. This is accomplished by intermittently issuing speed and vectoring commands.

Figures C-2 and C-3 show the range and locations of speed and path control that can be exercised by the ATC system along the arrival routes for Chicago O'Hare (Runway 32) and San Francisco (Runway 28) respectively in order to make the aircraft adhere to its planning. For efficiency, the control procedures shown in the figures are based on employing delay fans for path control and not permitting speed increases once they have been reduced[10]. These control procedures are based on the currently used speed profiles at respective airports and the allocated airspace for vectoring.

In addition to the aircraft flying time deviations, resulting from the ground speed estimation uncertainties, the other deviations that affect the arrival times on the final are as follows:

1. The time deviations from navigation described in previous section, which affect an aircraft's final arrival time only when the aircraft changes it track.

2. The surveillance and pilot/controller communication delays which have an impact on the aircraft desired times on final when a command is used.

The analysis presented in the following paragraphs first examine the impact of each ATC uncertainty individually, and then a final error and control relationship is developed for procedures of Figures C-2 and C-3 to estimate the delivery dispersions at the gate.

### C.5.2 Ground Speed Errors

An aircraft generally flies an indicated airspeed, whereas the ground system establishes landing times based on its ground speed. The uncertainties in the aircraft's ground speed estimation on the ground results from the quantization of IAS commands to 10 knots, IAS/TAS approximations as a function of altitude, instrumentation and the knowledge of the alongtrack wind components. In this analysis, the above errors have been assumed as airspeed errors of $\pm$ 6 knots ($2\sigma$) normalized from a uniform quantized speed error of 10 knots. The alongtrack wind error component is assumed as $\pm$ 10 knots ($2\sigma$). The time error that an aircraft would accumulate while flying over a certain distance using specific speeds (shown in Figures C-2 and C-3) due to airspeed errors is shown in Figure C-7. The corresponding alongtrack wind errors are shown in Figure C-8.

### C.5.3 Surveillance Errors

The radar surveillance errors (i.e. neglecting display and operator errors by assuming computer derived surveillance function) were calculated from the range and angle of aircraft at each control point with respect to the ASRs at Chicago and San Francisco, and the ASR accuracy assumed in Appendix A. These errors were then converted into time errors using the aircraft's speeds at those points. The two sigma time errors due to surveillance at each command point for Chicago is given in Table C-2 and for San Francisco in Table C-3.

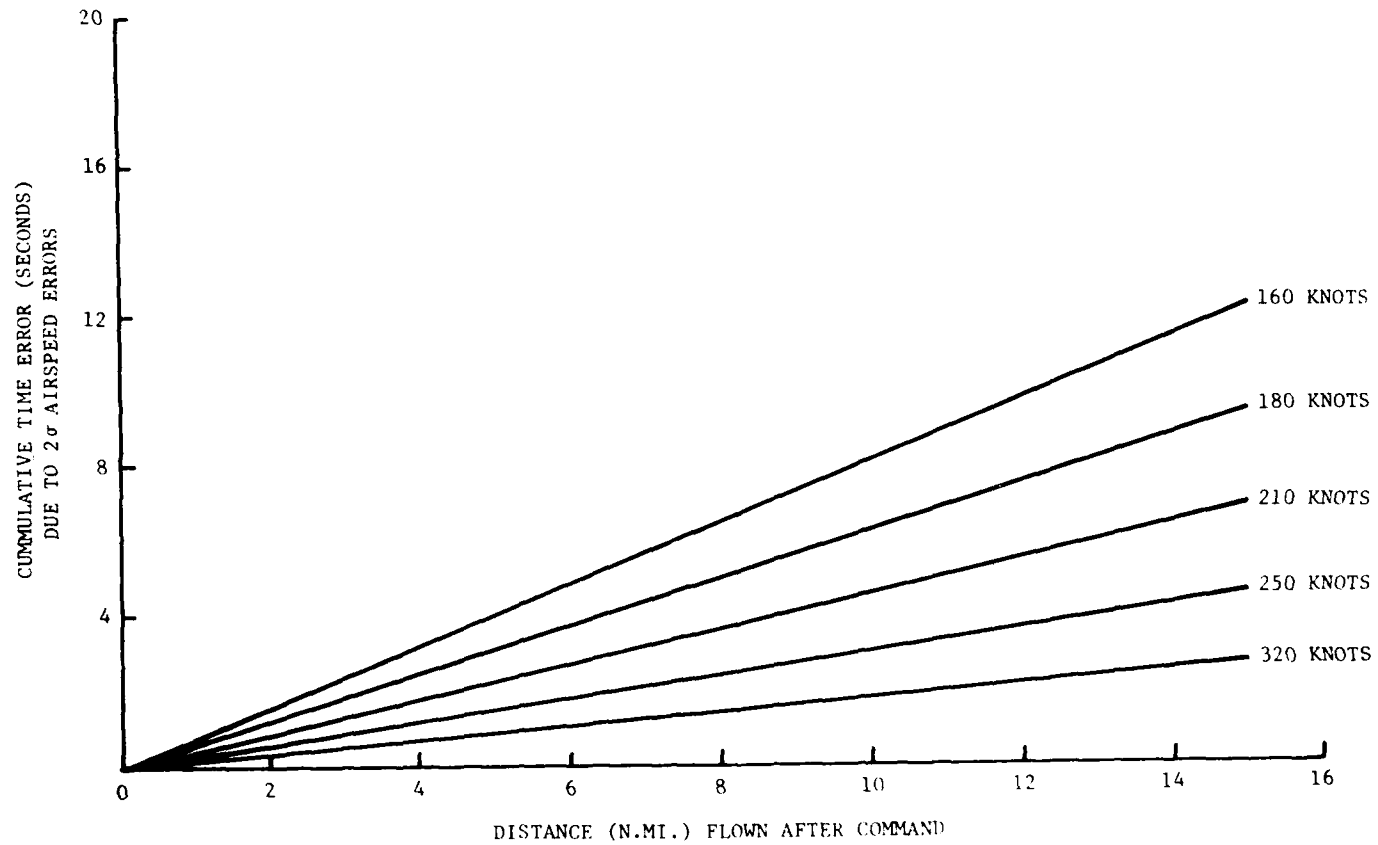



**FIGURE C-7**
**EXPECTED TIME ERROR ACCUMULATION DUE TO AIRSPEED ERRORS**
**(SPEED ERROR 1 $\sigma$ = 3 KNOTS)**

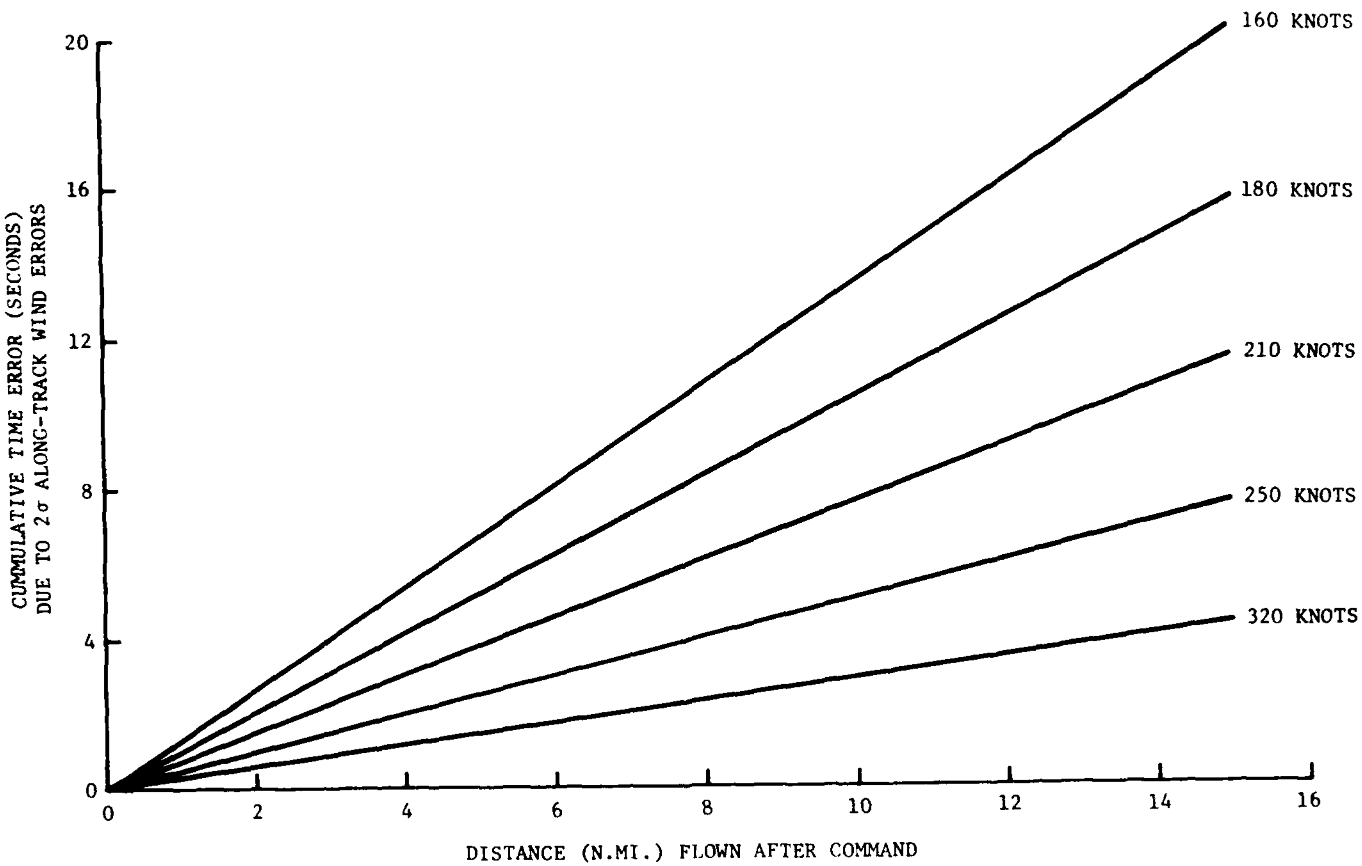



**FIGURE C-8**
**EXPECTED TIME ERROR ACCUMULATION DUE TO ALONG-TRACK WIND ERRORS (1 $\sigma$ = 5 KNOTS)**

TABLE C-2
TIME ERRORS DUE TO SURVEILLANCE FOR CHICAGO O'HARE

| Command Point | $\pm 2\sigma$ Time Errors (Seconds) |
|---|---|
| WP1 | 2.7 |
| WP2 | 2.2 |
| WP3 | 2.8 |
| First Heading Point | 2.1 |
| Second Heading Point | 2.0 |

TABLE C-3
TIME ERRORS DUE TO SURVEILLANCE FOR SAN FRANCISCO

| Command Point | $\pm 2\sigma$ Time Errors (Seconds) |
|---|---|
| WP1 | 1.9 |
| Intermediate Speed Control Point | 1.5 |
| WP2 | 2.0 |
| WP3 | 3.2 |
| First Heading Point | 2.3 |
| Second Heading Point | 2.2 |

### C.5.4 Communication Delay Errors

For a 7 seconds communication delay, the time errors are negligible in straight flight. However, there is a small impact of time delay involved in initiating turns at a constant ground speed, as a function of turn angle (by taking into an account the effect of appropriate gain described in Reference 10).

## C.6 Evaluation Of Time Error At The Gate

The amount of control that can be achieved through speed contr by assigning speeds between the ranges at the speed contro points and through path control using delay fans (shown in Figures C-2 and C-3) is represented by vertical lines in Figure C-9 for Chicago geometry and in Figure C-10 for San Francisco geometry. Also, shown in these figures are the two sigma total accumulated time errors obtained by statistically combining the various error components using the root sum square (RSS) method. The step increases in these errors are due to navigation, pilotage, surveillance and communication delays that come into play every time an aircraft changes it course or gets a commnand.

Other ATC system error components and environment remaining the same, the impact of navigation errors for the following four navigation configurations have been analyzed. The first configuration assumes that the aircraft are equipped with general receivers, and use the existing navaids. A flight technical error of $\pm$ 3000 ft. ($2\sigma$) is assumed due to lower navigation accuracy. The second and third scenarios assume air carrier type aircraft with ARINC quality receivers and flight technical error of $\pm$ 1200 ft ($2\sigma$) using existing navaids without, and with the MLS. The fourth case assumes a highly accurate navaid located at the airport with the aircraft (equipped with high performance receivers) having flight technical error of $\pm$ 600 ft. ($2\sigma$).

As shown in Figures C-9 and C-10, the designed geometries provide enough control capability to not only compensate for the aircrafts' flying time deviations, but also could provide adjustments to the initial terminal area entry errors of $\pm$ 60 seconds$^{(2\sigma)}$. Consequently, under the current operations, both at Chicago and San Francisco, there is sufficient control due to path adjustments, that the aircrafts' flying time deviations up to the last turn on final can be easily wiped out. As such, the time errors at the gate would be what the aircraft accumulate over the distance between $WP_4$ and the gate, which is within the desired delivery accuracy objectives of $\pm$ 10 seconds ($2\sigma$).

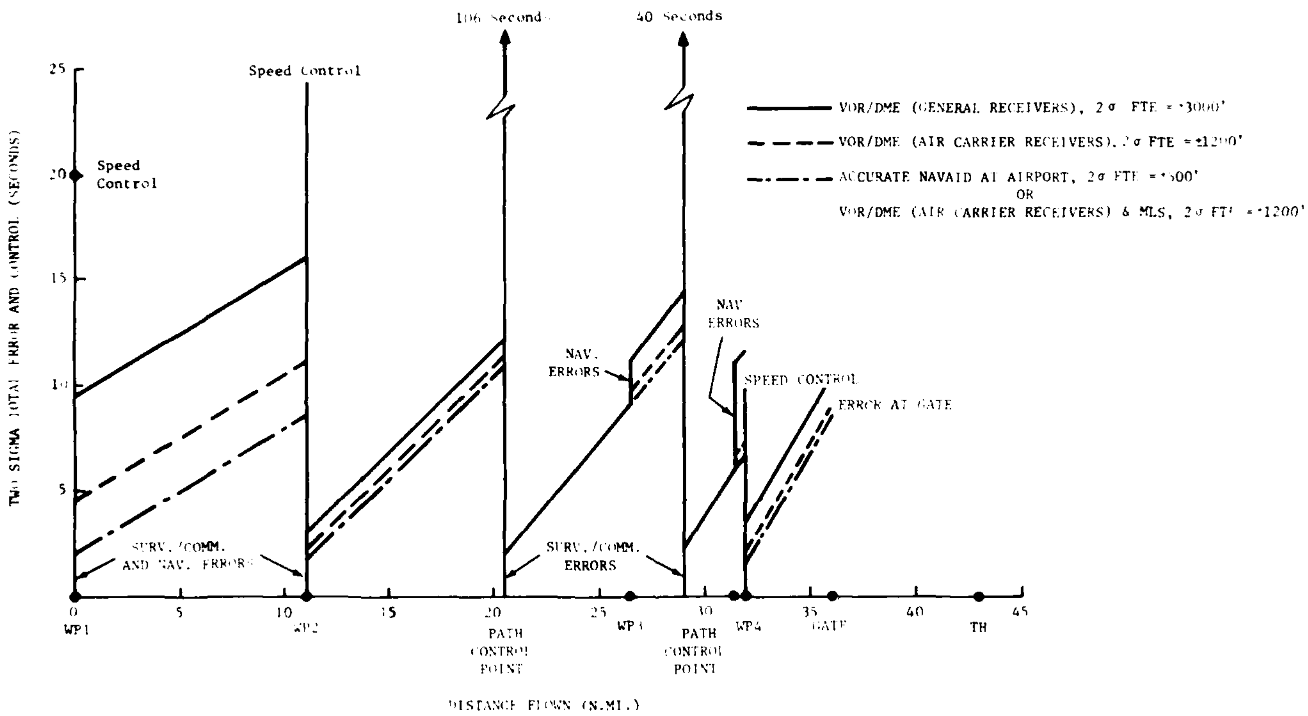



**FIGURE C-9**
**ERROR AND CONTROL DIAGRAM (WITH SPEED AND PATH CONTROL)**
**CHICAGO O'HARE**

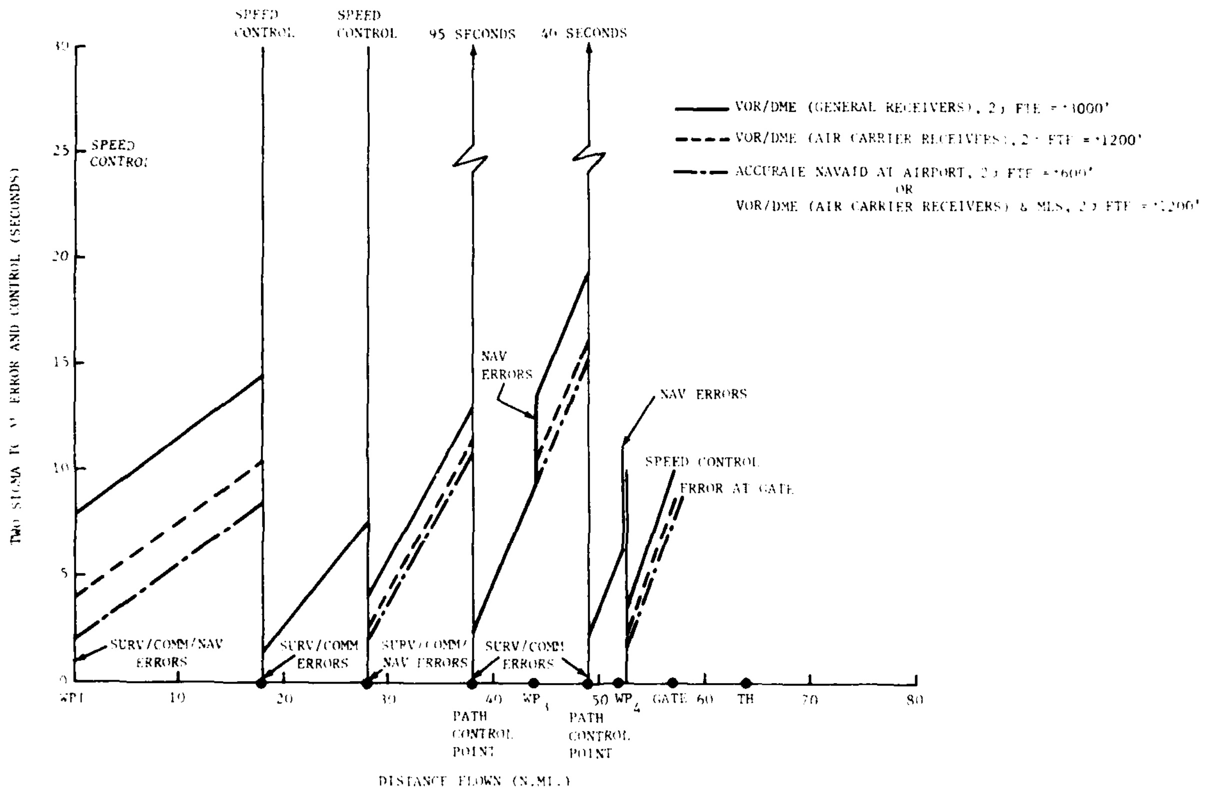



**FIGURE C-10**
**ERROR AND CONTROL DIAGRAM (WITH SPEED AND PATH CONTROL)**
***SAN FRANCISCO***

Based on the control procedures of Figures C-2 and C-3, a controller would normally need to issue 6 commands per aircraft (assuming 2 commands per delay fan).

The above results indicate that some path control would always be needed to accomodate TMA entry errors of $\pm$ 60 seconds ($2\sigma$) virtually independent of the navaid accuracy. As long as there is sufficient control available to limit open loop flying, the desired gate delivery accuracy of $\pm$ 10 seconds ($2\sigma$) can be achieved even with the present navigation system accuracy and layout, though this may require up to 6 commands per aircraft. The results also show that at airports with an all-air carrier operation, there would be a negligible difference in gate delivery accuracy achievable through the current navigation capabilities vs. a highly accurate airport-based navaid. This is because the airspeed and the alongtrack wind errors mainly affect the final error at the gate, and with these error components dominating the error budget, a highly accurate navaid at the airport provides negligible improvement in the overall performance.

## C.7 Fixed Path Speed Control Concept

In present operations, because the traffic includes different types and classes of aircraft, the controllers need path control to accommodate large aircraft variations and maintain the desired spacings. In the future, as more aircraft get equipped with flight management computers, and the traffic tends towards mostly air carrier operations at high density airports, the ATC could deal with a homogeneous situation in terms of avionics characteristics. There is also some emphasis to develop ATC concepts, based on the ground system simply providing the aircraft with times to arrive at specified points in space; and the aircraft is then responsible to meet these times through its own onboard management.

In order to use such a concept efficiently in peak traffic, the aircraft would be expected to maintain an ATC prestablished space/time relationship in the horizontal plane i.e., the aircraft would be required to achieve predetermined times at fixed points along the desired routes. The only means of control available for spacing would be through ground speed adjustments.

A ground-based fixed path speed control system may be considered as a viable mode of operation in the foreseable future, because such a concept could make the best use of high navigation accuracy and sophisticated aircraft capabilities, reduce

controller and pilot workload without affecting the operating procedures. In this section, the impact of navigation accuracy on a fixed path speed control concept has been examined. The current geometries of Chicago and San Francisco have been modified to provide speed variability within the existing range and airspace constraints.

### C.7.1 Fixed Path Speed Control Geometry

The geometries of Figures C-2 and C-3 were modified based on only speed control procedures and are shown in Figure C-11 for Chicago O'Hare and C-12 for San Francisco. These procedures assume that all the planning and control would be provided by the ground and no speed increases would be permitted. Since in this concept, the only means of control is through speed adjustments suggested by the ground, the concept can easily adapt to an airborne derived system, whenever such a concept would be acceptable.

### C.7.2 Evaluation Of Time Errors At The Gate

Corresponding to the speed ranges shown in Figures C-11 and C-12, the amount of control that can be achieved by assigning speeds between these ranges at each speed control point is shown by vertical lines in Figures C-13 and C-14 for Chicago O'Hare and San Francisco respectively. The figures also show the two sigma total error accumulations between each control point. As before, the step increases are due to navigation, pilotage, surveillance and communication delays.

The same navigation system scenarios of Section C-6 have been examined in the fixed path speed control concept. As shown in Figure C-13, the excess controllability beyond what is needed for flying time deviations at Chicago is about 26 seconds. It is about 60 seconds at San Francisco (Figure C-14). Therefore, even though an initial arrival error of $\pm 60$ seconds ($2\sigma$) pose no problem at San Francisco, the Chicago control geometry cannot accommodate TMA entry errors of more than $\pm 30$ seconds ($2\sigma$). The Figures C-13 and C-14 also show that there is enough control available to compensate for flying time deviations in the initial stages of flight through the TMAs. However, as the aircraft approach the final, the speed control capability reduces significantly. Consequently, the desired accuracy of $\pm 10$ seconds ($2\sigma$) at the gate will not be possible for aircraft equipped with a general receiver. For an all-air carrier operation where the aircraft have ARINC quality receivers, the achievable gate accuracy with the existing navaids is not much different from what can be expected from a highly accurate

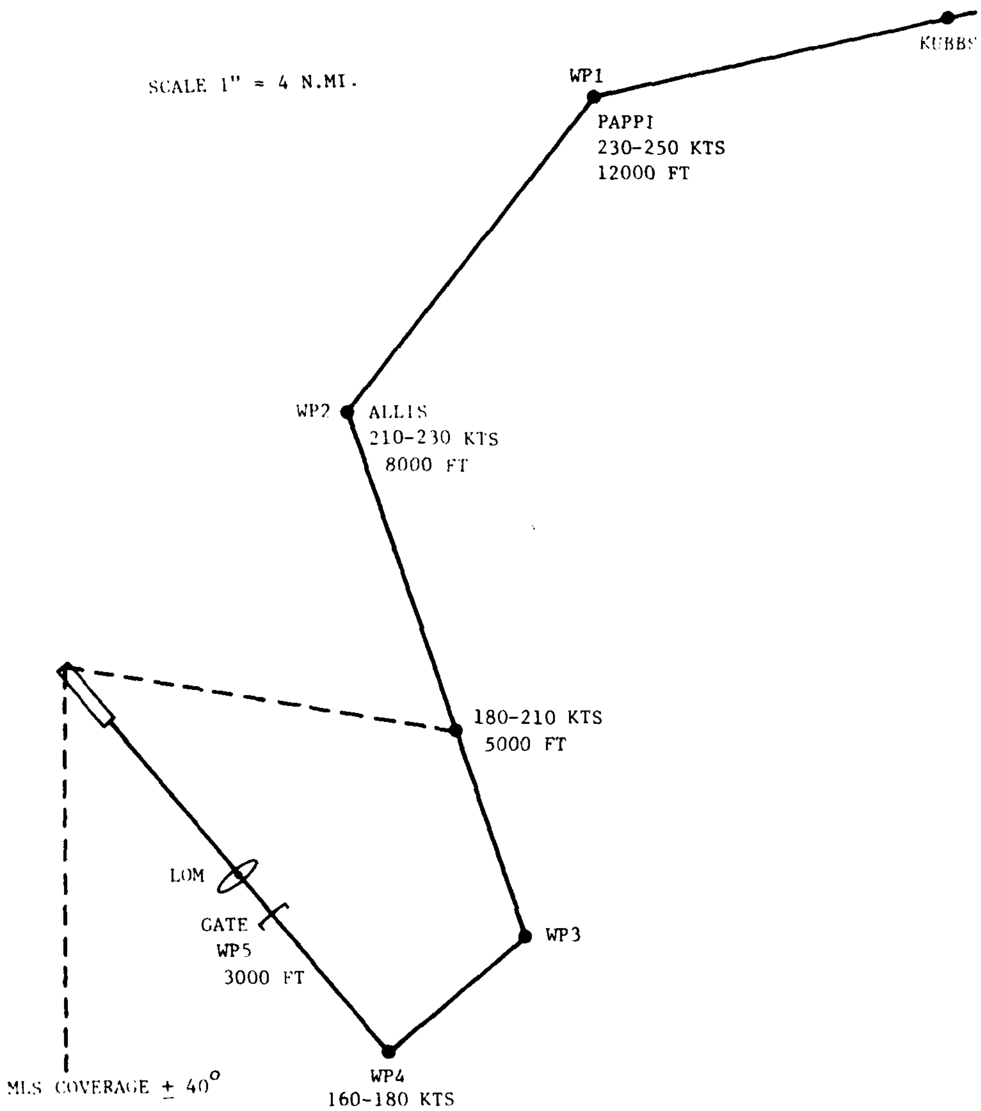



**FIGURE C-11**
**CHICAGO O'HARE SPEED CONTROL GEOMETRY**
**(FOR RUNWAY 32)**

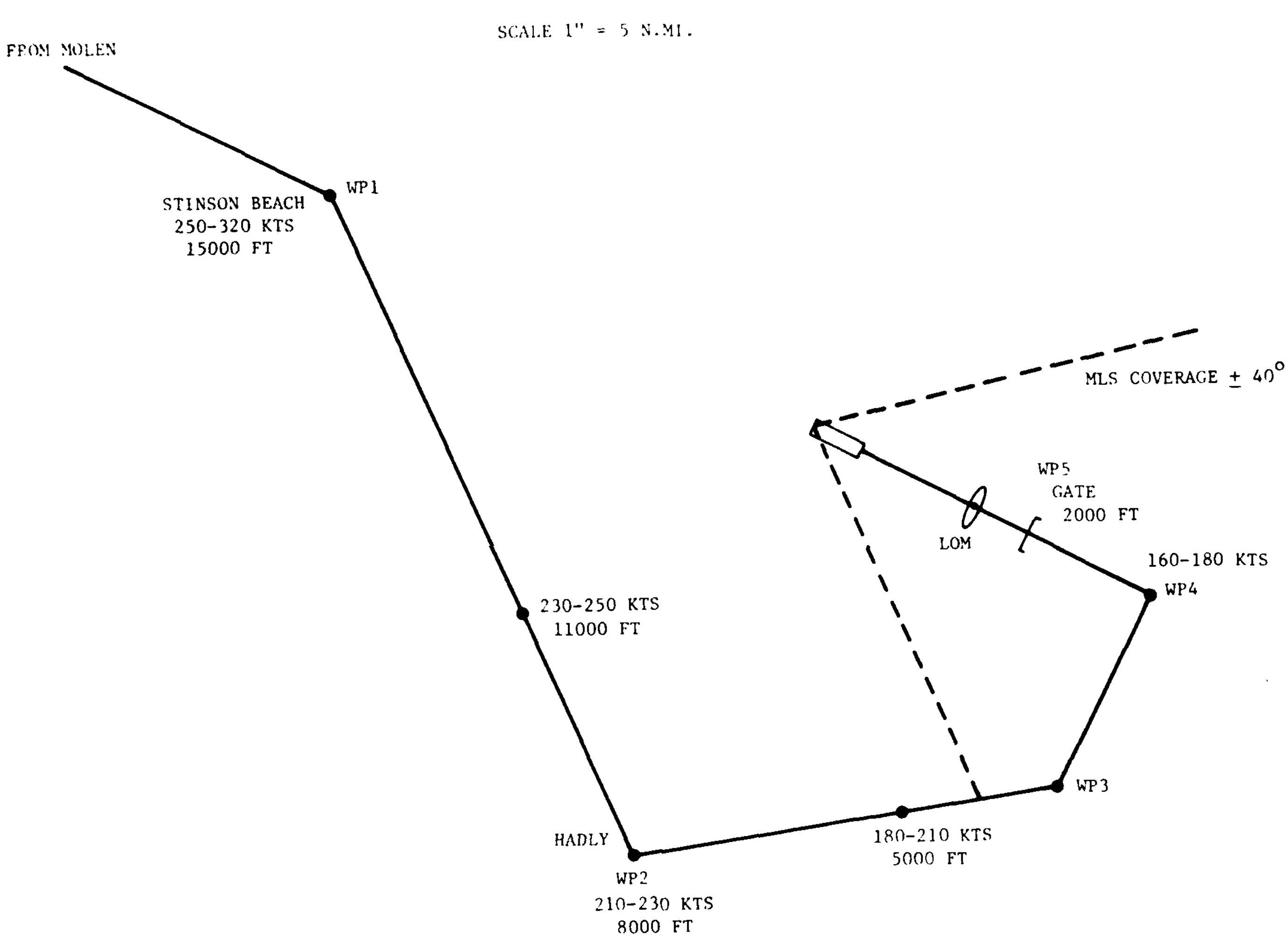



**FIGURE C-12**
**SAN FRANCISCO SPEED CONTROL GEOMETRY**
**(FOR RUNWAY 28)**

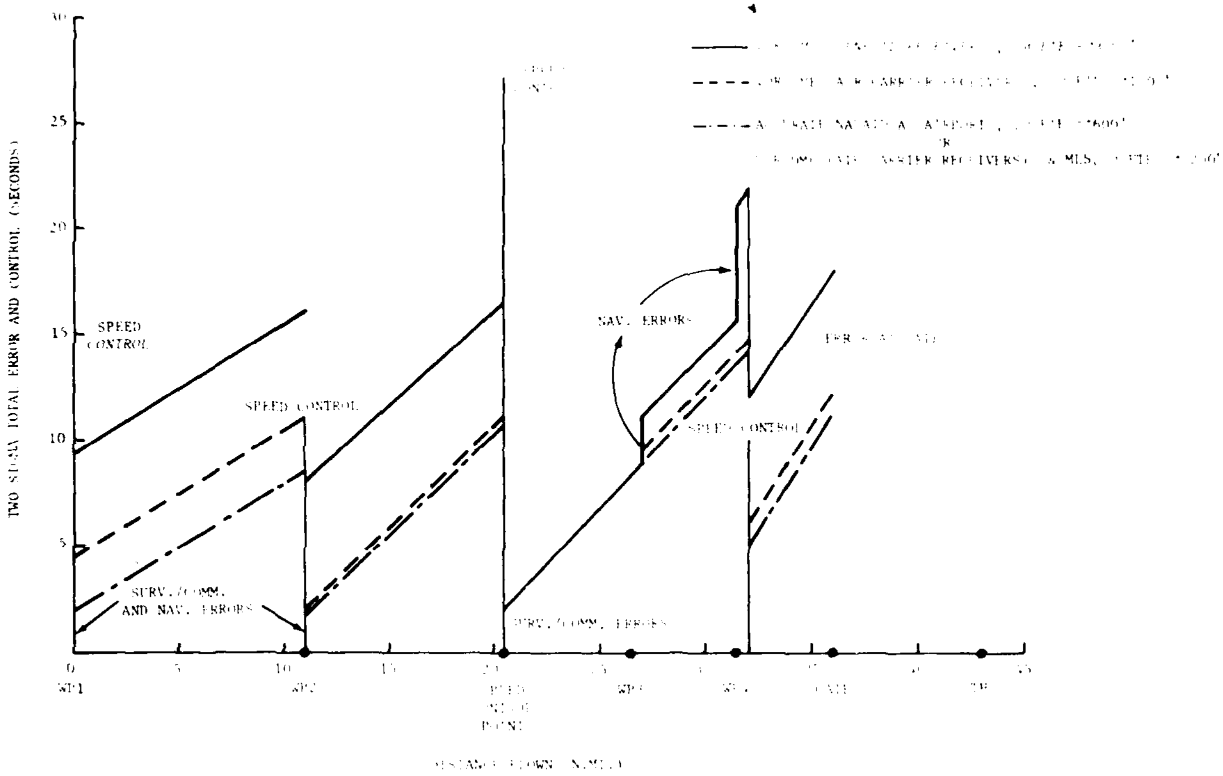



**FIGURE C-13**
**ERROR AND CONTROL DIAGRAM (WITH SPEED CONTROL)**
**CHICAGO O'HARE**

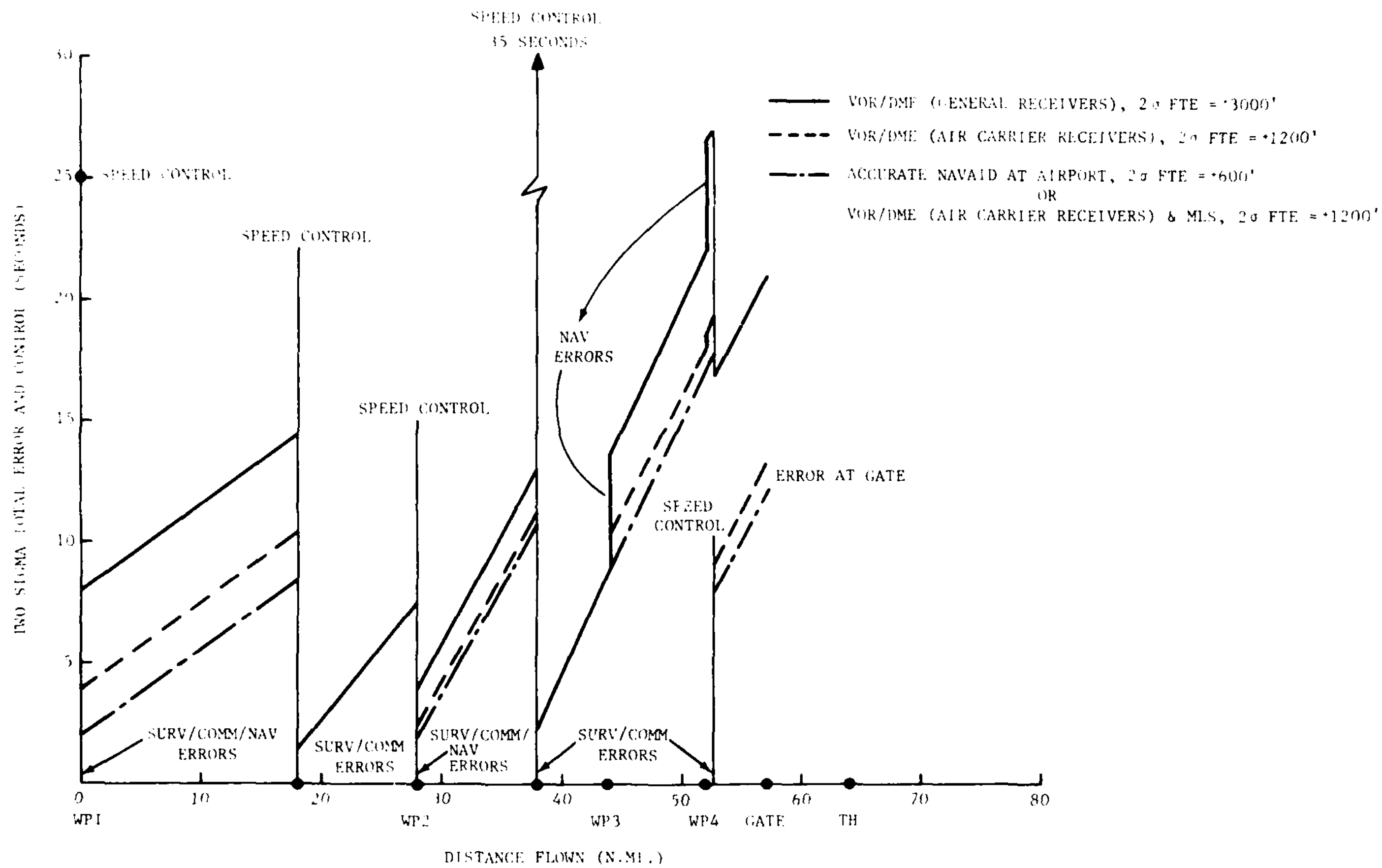



**FIGURE C-14**
**ERROR AND CONTROL DIAGRAM (WITH SPEED CONTROL)**
**SAN FRANCISCO**

navaid at the airport. The gate delivery accuracy is the same if an MLS is used in conjunction with the existing navaids or a highly accurate navaid is used at the airport.

The results indicate that if a fixed path speed control concept is to be used, the terminal area entry errors would have to be reduced to within $\pm 30$ seconds ($2\sigma$). Since the aircraft would be able to navigate all the way to touchdown with mainly speed adjustments, the number of controller commands would be reduced from nominally six to four i.e., a 33% reduction in controller workload. The results also show that regardless, of the navigation system accuracy, a gate delivery accuracy of about $\pm 12$ seconds ($2\sigma$) can be achieved through speed control. In order to achieve the desired gate delivery accuracy of $\pm 10$ seconds ($2\sigma$), some additional control will be needed near the gate. This can be provided through either a small path control area near the gate in a ground-based system, or a small allowance for speed increases in the airborne derived system.

C.7.3 Navigation Accuracy Requirements

In light of the above discussions, for an all-air carrier operation, the existing navigation aids are adequate for achieving the desired capacity related objectives, and the performance improvements offered by a highly accurate navaid at the airport are insignificant. As shown earlier, since the geometry also impacts the overall performance, if an airport-based navaid is to be used, in order to be compatible with the exsiting navaids, the accuracy requirements for such a navaid can be determined by interpolating the performance results of navigation sensitivity analysis as derived below

$$2\sigma\theta = \pm 0.6^{o} \qquad \text{(C-9)}$$
$$2\sigma\rho = \pm 0.14 \text{ nmi} \qquad \text{(C-10)}$$
$$2\sigma \text{ FTE} = \pm 1200 \text{ ft} \qquad \text{(C-11)}$$

C.8 Navigation Error Sensitivity Analysis for Aircraft Requiring Minimum Maneuvers in Terminal Areas

It has been illustrated in the analysis in this section that the errors due to navigation affect the dispersions on final, only during aircraft maneuvers. The geometries (for Runway 32 at Chicago O'Hare and Runway 28 at San Francisco) analyzed earlier could have the maximum impact of navigation accuracy due to the largest number of turns involved over the arrival route structures. Therefore, the accuracy established above represents an upper bound on navigation system requirements. In the next paragraph, navigation error sensitivity results are

presented for the aircraft arriving over routes requiring minimum maneuvers, i.e., where the impact of navigation accuracy over final dispersions would be minimal.

Figures C-15 and C-16 show the arrival geometries for Runway 14 at Chicago O'Hare and Runway 19 at San Francisco respectively[1]. The worst-case cummulative time errors due to navigation over these routes are shown in Figure C-17 for Chicago and Figure C-18 for San Francisco. As shown in these figures, the $2\sigma$ cummulative time errors, due to navigation over the entire arrival paths in Figures C-15 and C-16, is less than 10 seconds in a homogeneous environment. As shown in the analysis earlier, these magnitudes of error would have hardly any impact on the total dispersion on the final approach. Moreover, the figures also show that the cummulative errors due to navigation, for the aircraft over the least maneuverable routes, are not very sensitive to the navigation system accuracy. Therefore, the exisiting navigation capabilities are sufficient to permit the aircraft to navigate over such routes under heavy traffic without affecting capacity.

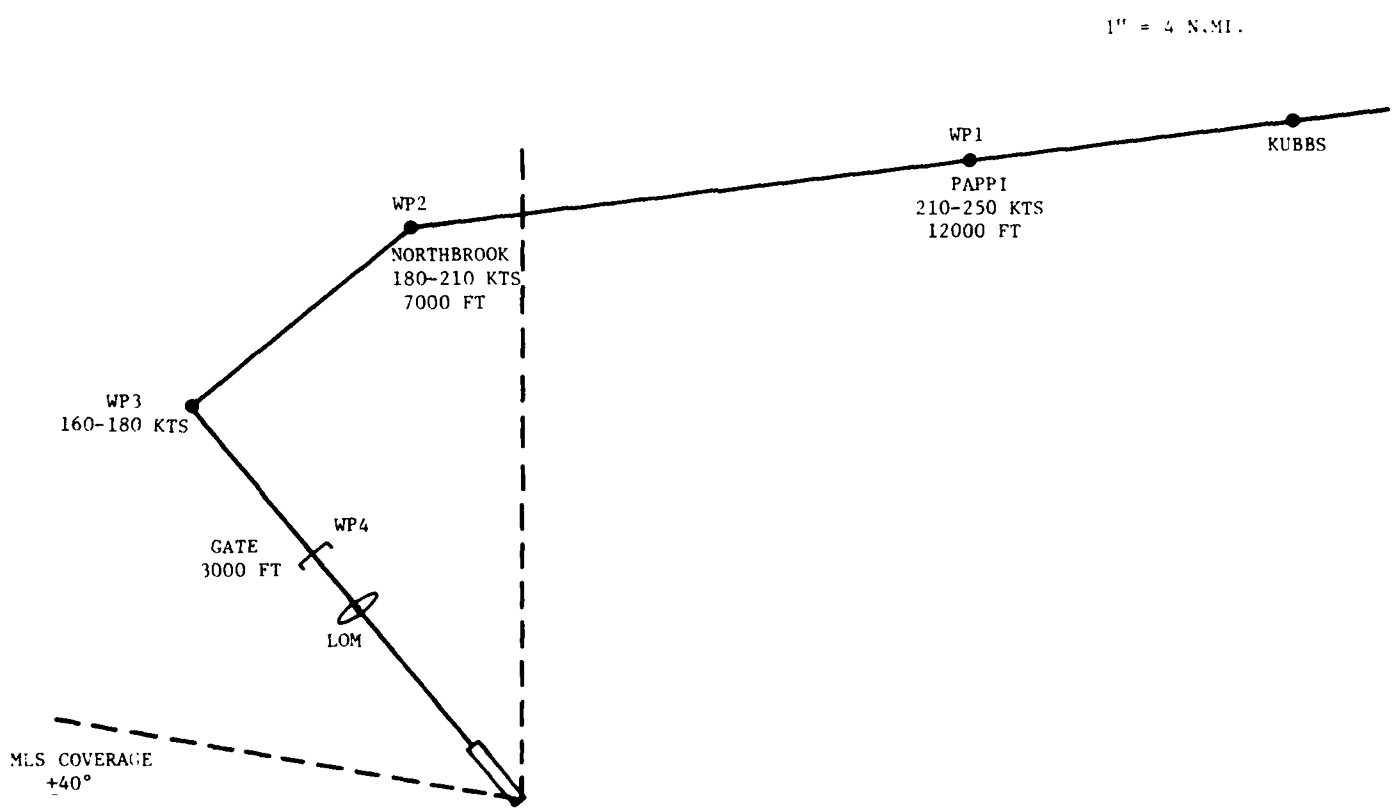



**FIGURE C-15**
**CHICAGO O'HARE ARRIVAL GEOMETRY (FOR RUNWAY 14)**

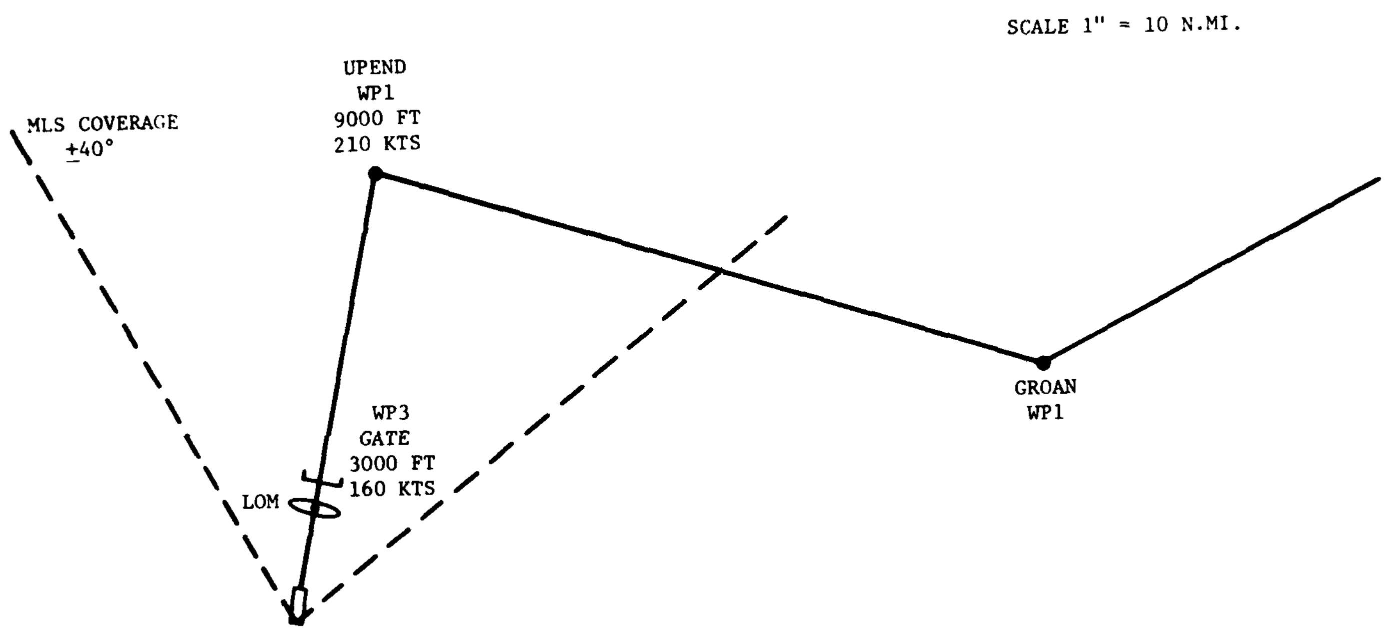



**FIGURE C-16**
**SAN FRANCISCO ARRIVAL GEOMETRY**
**(FOR RUNWAY 19)**

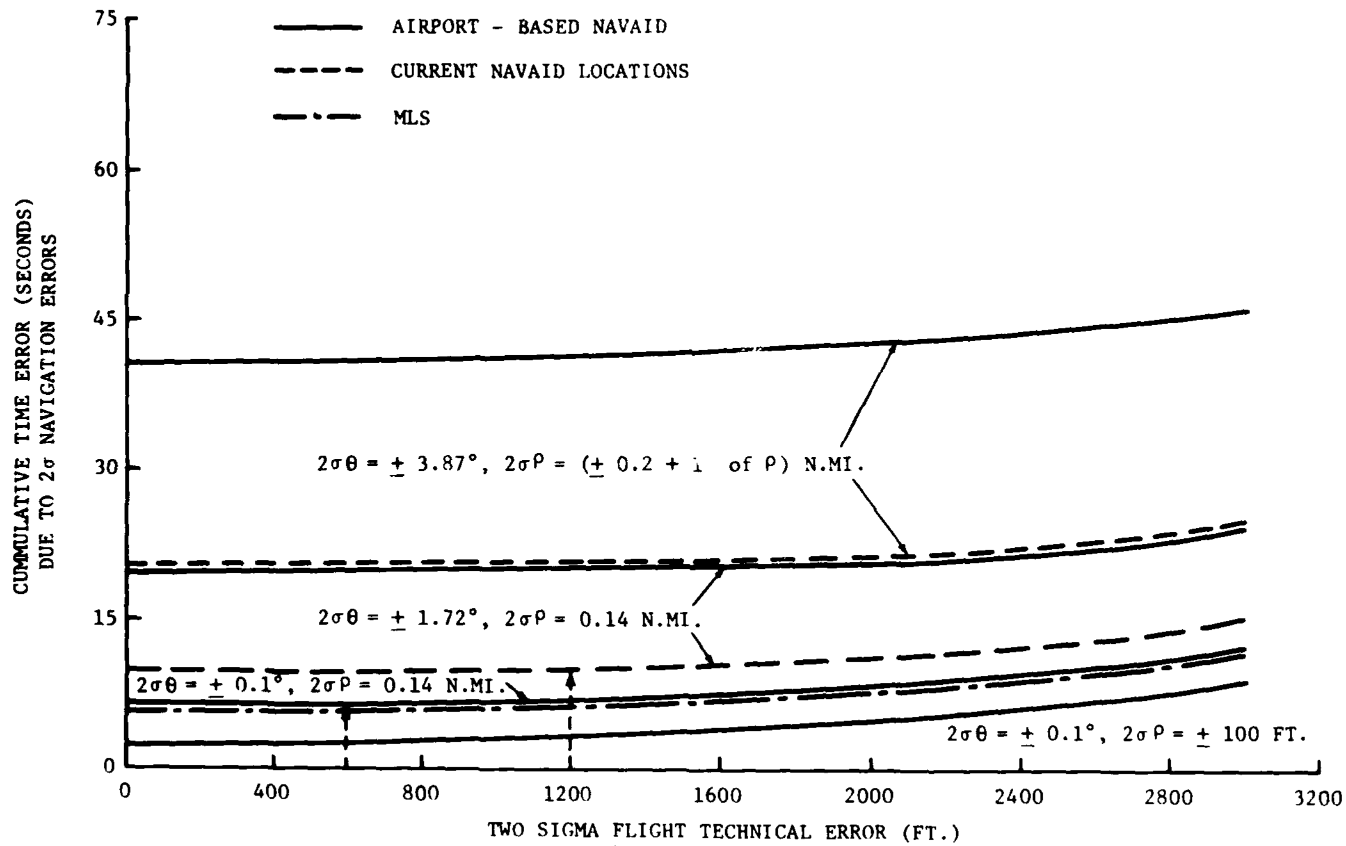



**FIGURE C-17**
**WORST CASE NAVIGATION INDUCED ERRORS AT THE OUTER MARKER AS A FUNCTION OF FLIGHT TECHNICAL ERROR (CHICAGO O'HARE RUNWAY 14)**

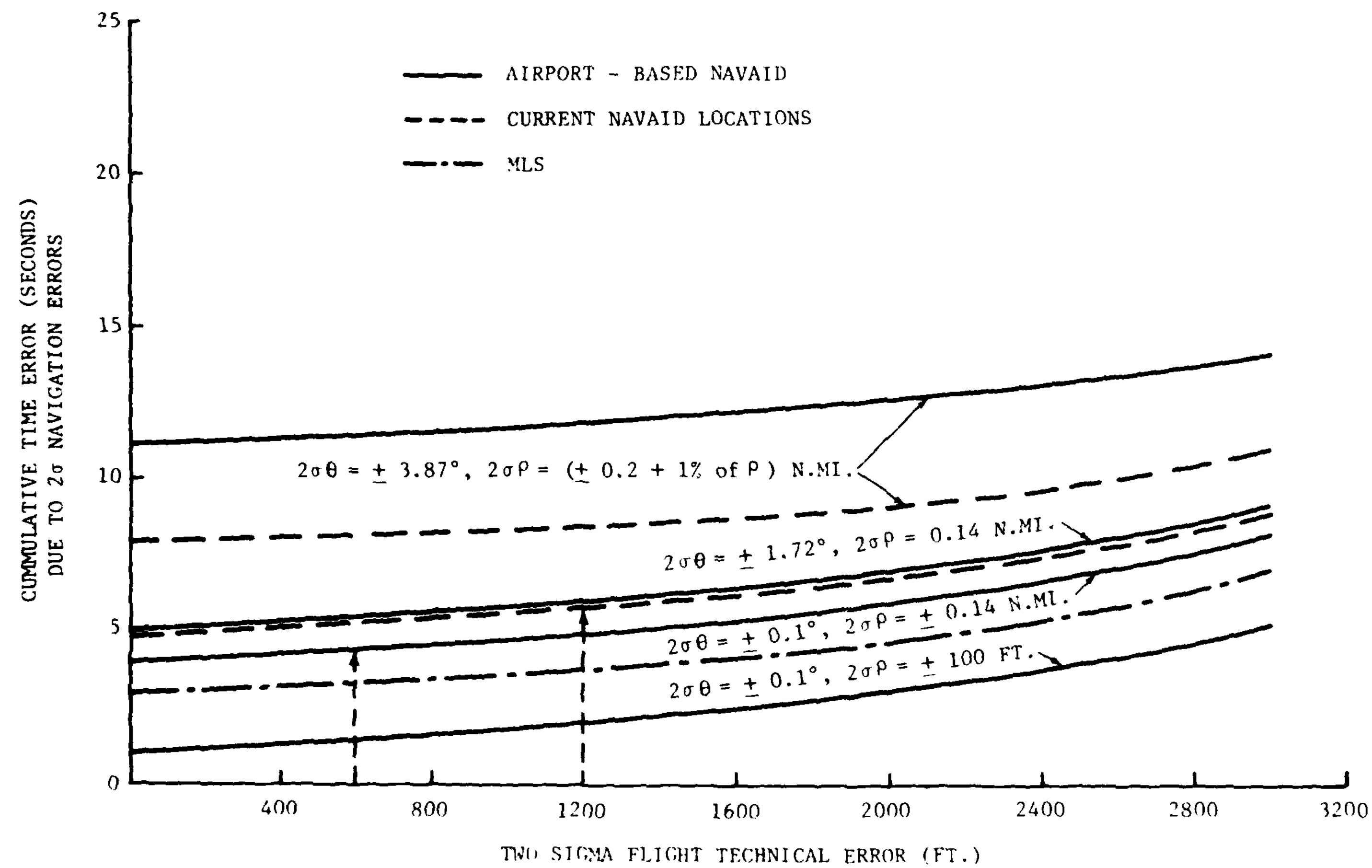



**FIGURE C-18**
**WORST CASE NAVIGATION INDUCED ERRORS AT THE OUTER MARKER AS A FUNCTION OF FLIGHT TECHNICAL ERROR (SAN FRANCISCO RUNWAY 19)**

## APPENDIX D

## NUMBER OF SIMULTANEOUS USERS

Due to simultaneous parallel runway arrival and departure operations at Chicago O'Hare, the maximum user requirements would be at this airport. The evaluation presented in this section assumes parallel approaches on runways 32 R and L, and departures taking off from 27L. Using the typical speed profile of Figure C-2, the average flying time for north arrivals is 1074 seconds and for south arrivals the nominal time is 792 seconds. For a homogeneous traffic environment, requiring 3 nmi IFR separation on final (corresponding to 74 seconds at an average speed of 145 knots over the final segment), the single runway arrival capacity would be 40 aircraft per hour assuming a buffer corresponding to two sigma interarrival error of $\pm 16$ seconds (based on aircraft landing time error dispersion of $\pm 10$ seconds). Under peak conditions with no gaps in the arrival stream, for the above TMA flying times, one could expect a maximum number of 21 arriving aircraft at any instant of time. During the same time period, assuming the aircraft depart every minute independent of arrivals, a maximum number of aircraft on departure routes in the TMA can be about 18. If all of these aircraft are navigating, the navigation system would need to provide guidance to about 40 aircraft at any one time. Allowing some allowance for holding, the maximum number of aircraft simultaneously using an airport based navaid is 50.

## APPENDIX E

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